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INSTITUTE OF TECHNOLOGY

AN APPLICATION OF A COMPUTER OPTICAL
DESIGN PROGRAM

THESIS

AFIT/GEP/PH/82D-26   William J. Welker, Jr.
                           Captain   USAF

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THESIS

Presented to the Faculty of the School of Engineering

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by

William J. Welker, Jr., B.S.

Captain   USAF

Graduate Engineering Physics

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Preface

The purpose of this study was to locate an optical design computer program for use at AFIT and to apply the program to an optical design project. I chose this topic because of my interest and background in both optics and computers. I have had numerous classes in optics and much practical experience as a camera repairman. I had not previously had any experience in optical design. I have enjoyed much experience in computer programming and never pass up a chance to work on a computer project.

I wish to thank my advisor, Lt Col John Erkkila for serving as an intermediary with the author of the computer program, Dr. John Loomis, and seeing to it that the program was installed at AFIT. I would like to thank Mrs. Linda Stoddard, AFIT research librarian, for locating countless, obscure articles during my literature survey. I am indebted to Dr. Douglas Knight, President of the Questar Corporation, for providing me with the data necessary to model the Qeustar telescope on the computer. And finally, I wish to thank my wife for bearing with me during this project and remembering how it was when she did her thesis. Her inspiration and support were essential.

<div align="right">

William J. Welker, Jr.

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Abstract

A survey was made of existing optical design computer programs, and one selected for use at AFIT. The program selected is named FALCON, and a number of its capabilities are described.

The program is then used to develop a lens system whose effective focal length is 21 meters and whose overall length (first surface to focal plane) is about 45 cm. The purpose of the lens is to accept two laser beam samples from a source (i.e., a phased array telescope) and focus the beams to a diffraction limited spot. (The two beams interfere and the resulting interference pattern would be analyzed.) A standard 3½ inch Questar* telescope is used as the first optical element and its 1.27m focal length is extended some 16 times by adding lenses to the focal cone. A second design is made using entirely refractive optics to overcome a central obscuration problem caused by the secondary mirror of the Questar. FALCON is used exclusively to do all the design work.

*Questar is a trade mark of the Questar Corporation, New Hope, Pennsylvania.

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I. Introduction

Background

The development of a large, phased array, space-borne High
Energy Laser (HEL) will depend on the solution of many technical prob-
lems, one of which is the phase locking of all the apertures. Briefly,
a phased array HEL will consist of several mirrors (3 - 5m diameter)
positioned to synthesize a single, large mirror. Synthesis of large
mirrors in this manner overcomes the technological problems that would
be encountered if a single large ($\approx$10m diameter) mirror were to be
made. (This is a gross oversimplification, but the scope of this
problem does not deal with the specific mirror development.) Thus,
with the smaller mirrors forming the primary of a large telescope, one
must now adjust each mirror, continuously, such that the beam from each
is in phase and the energy of the resulting summed beam can be focused
and deposited on target.

It is assumed in this document that the phase determination will
be done by sampling the beams from the edges of two mirrors at a time
and that the samples will be directed into an appropriate optical system
for analysis. This document is concerned with the optical system that
will receive the two sample beams and provide an image so that a

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suitable detector coupled to a computer can provide the information needed to determine the phase relationship.

The development of an optical system requires a knowledge of the object characteristics or the properties of the light that will enter the system, and a knowledge of the desired image characteristics. The problem reduces to that of applied geometric optics. One must then use the techniques of lens design to develop the system and optimize that design to reduce the aberrations and ensure that the image formed possesses the required characteristics.

In decades past, a lens designer would start with an educated guess or with a known lens, and labor with pencil and logarithm as he traced rays and calculated aberrations. Based on the results, he repeatedly made small changes in design until he was satisfied. Today, computer programs are used to do all the laborious calculations, and some programs will even make the small changes and recalculations until a set of predetermined design tolerances are met. Therefore, there is no need for a designer to design by hand, unless of course he wishes to see it for himself!

Problem

The problem is in two parts: (1) find a computer optical design program suitable for use at AFIT, and (2) use the program to design a system for use in the phased array development problem discussed above.

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Assumptions

The computer optical design program should be complete and fully operable so that no computer code need be written (except that job control language necessary to interface the program with the AFIT computer system.) No funds are to be expended on the purchase or lease of a program due to the lack of funds available for such purposes and the long lead time needed to request appropriations. The program must, therefore, be free of charge.

A standard Questar* telescope will be taken as the first element in the design. The Air Force Weapons Lab (AFWL) suggested the use of a Questar since one or more of them are available at the weapons lab for prototyping the design. The system will be designed in air with an index of refraction equal to 1.00. The overall length of the system will be about 45 cm (18 inches) but this length is not a formal requirement.

Approach

A survey was made for the computer program and the results are presented in two parts: a description of the program chosen will be found in Chapter II and a compendium of all the programs found in the survey is delegated to Appendix A. Chapter III outlines the problem for which the design is to be made and develops the requirements on the design. Chapter IV discusses design by geometrical optics and the diffraction effects that are to be observed. The criteria for image

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assessment are developed. Chapter V is development of the design. The Questar will be modeled, and a solution to the problem using a single lens will be presented for comparison with the final design tnat follows. The final design is critiqued as to tolerances and construction of the system. Chapter VI deals with replacing the design with an all refractive system.

II. The Computer Program

A complete survey of all the optical design computer programs found during the course of this research is found in Appendix A. The purpose of this chapter is to describe the chosen program and explain some of its features.

The program is named FALCON. FALCON was written by Dr. John Loomis while he was a graduate student at the Optical Sciences Center, University of Arizona, during the period from 1975 to 1980 (21:1). The program was apparently named FROLIC when it was first under development (13:56), and as such may have been begun by another person or group. The literature is unclear on this point. Regardless of FALCON's origin, Dr. Loomis attempted to pattern it after a larger, commercial program called ACCOS V (see Appendix A). This appears largely to be the only attempt by any programmer to develop uniformity among programs, although another program, COOL/GENII, uses an old style of ACCOS V input specification (22:6).

FALCON is a program to assist the designer in the design task rather than an automatic design program as are ACCOS V and COOL/GENII. FALCON has no "merit function" (see Glossary). The user inputs the lens description, executes various commands to see the results of the design, and makes manual changes to improve the lens. This is not a serious drawback to the user and, in fact, is really an aid to the novice designer who needs to see the intermediate results of his or her actions. The use of a merit function in the automatic design programs is not entirely foolproof anyway, and one must exercise care in the

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choice of the merit function if the program is to converge on an acceptable design. This point is driven home in an example problem conducted by Juergens (15:348-362). Juergens posed a problem that began with a specific lens and asked the participants to modify the design into two different configurations. The results were as varied as the number of participants and many different solutions were given even when the same program was used in the design. As best stated by Juergens (15:353):

> The problem was successful in demonstrating that a computer can drastically change a given lens form in a search for the optimum lens form for a new set of specitications. The problem also dramatically showed that the lens design program is not the sole determiner of the final solution, but that the designer who controls and manipulates the field, color, and aperture weightings and the constraints can significantly alter the direction the computer will take.

FALCON is, nonetheless, a very complete program without an automatic design feature. It is fully capable of handling refractive and reflective surfaces, diffraction gratings, spherical, aspherical and toroidal surfaces and Fresnel lenses. Surfaces may be decentered from the optic axis and tilted to any orientation. As many as five wavelengths can be specified for which rays are to be traced, and a nearly complete catalog of Schott optical glasses is built in. FALCON intarpolates the index of refraction for a specified wavelength when a Schott glass is indicated. (The catalog is known to be incomplete because a few Schott glasses were found to be missing when they were specified in listings during this study. The actual list of Schott glasses used in FALCON is not included in the FALCON user's manual.) FALCON can be used in both the batch mode (a lens specification on cards or card images in a disc file along with a list of commands sent at one time to the central processing unit) or in an interactive mode

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(time-sharing) where commands are processed in real time and the results displayed on the user's terminal. The interactive mode is designed for use on a Tektronix graphics terminal and all FALCON graphics can be displayed on the terminal. (Any terminal may run FALCON interactively, but the graphics can only be run in the line printer (low resolution) graphics mode.) The major FALCON capabilities and commands will be discussed below. This is by no means a complete description of FALCON. (The FALCON User's Manual is much more complete, although it was found to be in a draft stage having numerous errors, omissions, and fragmentary narration.) Enough information will be presented here that material in later chapters may be understood.

FALCON uses a standard, right-hand rectangular coordinate system. The Z axis is taken as the optic axis and light propagates from left to right in the positive Z direction. The YZ plane is called the tangential plane and is also a meridian plane. The XZ plane is called the sagittal plane. Some standard symbology and definitions are given in Figure 1. Distances are measured along the optic axis always from one surface to the next, be it the vertex of a lens surface or the center of an aperture stop or the object or image plane. The distance from the object to the first surface may be specified as any length, but if not, it is taken to be at infinity which is 10^{10} units. Axial and chief rays (see figure) are traced in the YZ plane. Any ray not lying in a meridian plane is called a skew ray. (A meridian plane is any plane containing the optic axis.) Heights of rays at any surface are the Y value of the ray's coordinate at the surface. A numerical subscript is added to indicate the surface number, and a bar over the top

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Figure 1. Coordinates and Symbology in FALCON.

indicates the quantity is that for a chief ray. Thus, Y_2 is the axial ray height at surface 2 and $\overline{Y}_2$ is the chief ray height. Angles are measured with respect to the optic axis and are generally symbolized by the letter u. (A notable exception is the angle of incidence which is the letter i.) A ray angle is positive if measured counterclockwise and negative if measured clockwise.

An optical system is specified by the LENS command. Each line following the LENS command is a surface. Termination of the LENS identifier is accomplished with the END command. The first line after LENS is line 0 (zero) and is taken to be the object. The specifications defining the field of view, distance to the first surface, maximum radius that a ray may enter the lens, and a list of wavelengths are all included on line 0. If a wavelength specifier (WV) is present, the

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order in which the five allowed wavelengths are listed is important. The first one is taken as the design wavelength. The second and third are used in chromatic aberration calculations. The fourth and fifth are additional wavelengths of interest. If no WV is present, the defaults are .58756, .48613, .65627, .43584, and .70652 μm. The field of view and the maximum radius are defined in terms of the axial and chief rays. The height at which the axial ray hits the first surface is given by SAY Y_1 where Y_1 is the numerical value in whatever units are being used. (If units are specified, they, too, appear on line 0. If not specified, the default units are centimeters for everything except wavelength which is always in microns.) The chief ray may be specified in two ways: (1) SCY $\overline{Y}_0$ $\overline{Y}_1$ specifies the ray starts at the object at height $\overline{Y}_0$ and enters the first surface at $\overline{Y}_1$, or (2) YFANG $\overline{U}_0$ $\overline{Y}_1$ specifies the field angle is $\overline{U}_0$ degrees and the ray enters surface 1 at $\overline{Y}_1$. Omission of $\overline{Y}_1$ allows FALCON to calculate the ray height needed at surface 1 to pass the chief ray through the center of the aperture stop. If the lens has no aperture stop specified, the chief ray is then directed to the vertex of surface 1.

All lines following line 0 are surfaces. They may be lens surfaces, dummy surfaces, or apertures or obstructions. All entries on a line (including line 0) may be in any order. A curvature may be specified by CV X or the radius of curvature by RD X where X is the appropriate value. A TH X parameter implies the distance (THickness) to the next surface is X. A CLAP X or COBS X specifies a CLear APerture or a Central OBStruction of radius X. (Rectangular CLAPS and obstructions can be specified by both an X and Y value after the acronym.

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X and Y are the semi-lengths of the sides in that case.) REFL identi-
fies the surface as a REFLector and ASTOP declares the surface an
Aperture STOP. SCHOTT (i) specifies the type of glass that follows the
surface, where (i) is the Schott glass name. GLASS followed by up to
five refractive indices can be used if a Schott glass is not wanted.
If no SCHOTT or GLASS identifier is used, the medium following the
surface is assumed to be air.

Several other identifiers may appear on a line. ASPH followed
by up to four coefficients give the surface an aspherical shape. CC X,
where X is a conic constant, makes the surface an ellipse, paraboloid,
or hyperboloid. CVY or CVX are used to account for a toric surface
where the axis of revolution is the Y or X axis respectively. In addi-
tion, a specific curvature or radius of curvature may be dispenced with
altogether in favor of a "paraxial solve".

A paraxial solve is a FALCON subroutine that solves for the
curvature of the surface to give a specified result. The result may be
a desired ray angle after refraction or a required ray height at the
next surface. A solve is also available that adjusts the distance to the
next surface so the ray height at that surface is a specific value. Ten
solves are found in FALCON and are summarized below:

Identifier	Type Solve	Parameter
PUY u	curvature	u is the desired angle after refraction or reflection.
SPY y	"	y is the desired ray height at the next surface.
PIY i	"	i is the desired axial ray angle of incidence at surface.
APY	"	Adjusts curve till i+u=0 (the aplanatic condition).
PCUY u	"	Same as PU^v but for Chief ray.

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Identifier	Type Solve	Parameter
SPCY y	"	Same as SPY but for Chief ray.
PICY i	"	Same as PIY but for Chief ray.
APCY	"	Same as APY but for Chief ray.
PY y	thickness	Adjusts distance to next surface so axial ray hits at y.
PCY y	"	Same as PY but for Chief ray.

A paraxial solve is a very powerful device. For instance, a PUY on the last surface will control the effective focal length and an SPY on the next to last surface will control the back focus. Used elsewhere, any angle of incidence or refraction can be controlled or an unknown distance can be automatically determined.

Gratings and Fresnel lenses are another feature of FALCON; however, no such surfaces are needed here and so, no description will be given. Also multiple-path configurations can be easily specified, as if one element in the system were a beamsplitter. This feature, too, is not needed here and will not be described.

The last line in the LENS listing is the END. This signals close of the LENS command and permits FALCON to process following commands. If the END is omitted, FALCON thinks each line thereafter is another surface and all identifiers that are not legal for a LENS list are ignored.

After the lens is specified, a number of evaluation and graphic commands can be executed. All would be useful in a general optical design and are therefore worth mentioning here if for no other reason than to indicate the available features. It will be seen in later chapters, however, that most of the geometric evaluation techniques and graphical output available in FALCON are not applicable to the design developed here. The commands that can best be summed up as "evaluation

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commands" are LEPRT, OCON, PARAX, FORD, RAY, PUPIL, and ZPOLY. The graphical commands, some of which produce both graphs and tabular data for evaluation purposes, are DISPLA, LAYOUT, FANS, SPOT PLOT, SPOT RED (and SPOT KED), GOTF, and WAMAP. Each is briefly discussed below. For clarity, example output in the form of a table or plot will be shown for a Maksutov telescope. The Maksutov design is that of Powell (30:40). A listing and diagram of the lens shown in Figure 9 serves two purposes. First, the reader can become familiar with the listing format as described above and second, it will make clear the LENS listing for a Maksutov telescope. This is needed because nowhere in this document will the data for the Questar Maksutov telescope be presented, see Chapter V.

LEPRT, (LEns PRinT), lists a table of important parameters of the lens. The sample of Figure 2 is self-explanatory. If present, the aspheric and conic or toric coefficients are also listed. In Figure 2, GIH stands for Gaussian Image Height.

OCON, (first order Operating CONditions), provides the EFL, BF, and LENGTH from the LEPRT but also identifies the primary surfaces. OB is object; EN, entrance pupil; FS, first surface; RF, reference surface; AS, aperture stop; LS, last surface; XP, exit pupil; and IM, image. See Figure 3. (The reference surface is a surface user defined for raytracing. Rays are aimed at the surface during a ray trace operation. For instance, the primary mirror of a telescope could be identified as a reference surface.)

PARAX, (PARAXial ray trace), provides a table of ray heights and angles at each surface of the lens for both a paraxial axial ray

LEPRT
--LEPRT

	EFL	BF	F/NBR	LENGTH	GIH
	75.4907	27.1254	8.39	20.1000	-6.4167

BASIC SYSTEM DATA   UNITS CM

SURF	CURVATURE	RADIUS	THICKNESS	MEDIUM	INDEX
0	0.000000	INFINITE	1.00000E+18		
1	-.068960	-14.501160	1.600000	BKG	1.531130
2	-.064420	-15.523129	18.500000		
3	-.018870	-52.994171	-18.000000	REFL	
4	-.035630	-28.066236	0.000000	REFL	
5	0.000000	INFINITE	27.125440		
6	0.000000	INFINITE	0.000000		

REFRACTIVE INDICES

SURF	N1	N2	N3	N4	N5	DF
1	1.531130	1.537058	1.528512	1.541658	1.527009	.268

WVLN	.58756	.48613	.65627	.43584	.70652

CLEAR APERTURES AND OBSTRUCTIONS

SURF		TYPE	CAY	CAX
2	OB		1.5000	
3	OB		1.0000	
4			1.7000	

Figure 2. The LEPRT for the Powell Maksutov.

	EFL	BF	F/NBR	LENGTH	GIH
	75.4907	27.1254	8.39	20.1000	-6.4167

OB	EN	FS	AS	RF	LS	XP	IM
0	1	1		1	4	5	6

Figure 3. OCON for the Powell Maksutov.

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and a chief ray at the wavelength specified. PARAX is most useful in examining a ray path for extreme angles or for crossing the axis where it was not intended. In addition, the ray height and refracted angle of the axial ray at the last surface can be used to calculate the physical longitudinal chromatic aberration (LChA) directly. (FALCON provides an axial and a lateral color based on third order theory but not the physical LChA. PARAX is illustrated in Figure 4.

PARAXIAL TRACE AT WAVELENGTH 1

SURF	AXIAL Y	CHIEF Y	AXIAL U	CHIEF U
0	0.000000	8.50000E+08	.000000	-.085000
1	4.500000	1.750000	.107646	-.013652
2	4.672234	1.728157	.004958	-.080033
3	4.763956	.247550	.174834	.089375
4	1.616948	-1.361206	-.059610	-.186375
5	1.616948	-1.361206	-.059610	-.186375
6	.000000	-6.416706	-.059610	-.186375

Figure 4. PARAX at Wavelength 1 for the Powell Maksutov.

FORD, (aberration table), is a list of third and fifth order aberrations. The third order aberrations are: SA3, spherical; CMA3, coma; AST3, astigmatism; DIS3, distortion; and PTZ3, Petzval field curvature. The fifth order aberrations carry a similar symbology: SA5, CMA5, AST5, DIS5, and PTZ5. (Although FALCON calculates the 3rd order aberrations by the method derived by Buchdal (3), they can be shown to be the classical Seidel aberrations easily calculated by hand, if so desired, by using the forms from Lea (20:93).) The transverse axial

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chromatic aberration, TaChA, is given in FALCON as PAC or primary axial

color. PAC is equivalent to the 3rd order equation for TaChA given by

Lea and an axial ray is used in its calculation. The transverse

lateral chromatic aberration, TChA, is given in FALCON by PLC or primary

lateral color. It is given by the same 3rd order equation as TaChA

but the relevant quantities are replaced by those from a chief ray. All

the equations for the 3rd order aberrations as given by Lea are found

in Appendix B for the convenience of the reader. The FORD table is

illustrated in Figure 5. The additional quantities listed in the table

are of little importance in this design and need not be discussed.

TRANSVERSE ABERRATIONS AT WAVELENGTH 1   UNITS CM

.000767	-.006385	-.003356	-.057618	-.039203
.002092	.007500	.000310	-.000391	-.000396
.000179	.001248	.002948	.000866	.002045
.006531	.010417	.002013	.004239	.004165
.003956	.002575	.009726	.009802	

SAE	CMA3	AST3	DIS3	PTZ3
SA5	CMA5	AST5	DIS5	PTZ5
SA7	PAC	PLC	SAC	SLC
ELCMA	TOBSA	SOBSA	M1	M3
N1	N2	PSA3	PCMA3	

Figure 5.   FORD aberration table for the Powell Maksutov.

RAY y x, (RAY trace), differs from a paraxial ray trace in the

PARAX command in that RAY traces a ray from any field point, in or out

of the meridian plane, through the lens. The ray enters the lens at the

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fractional coordinates given by y and x. Ray generates a table of
data detailing the ray intersection at each surface, its angle in
degrees of refraction or reflection and the optical path length of the
ray between each surface. RAY is most useful when LAYOUT is active
in which case the specified ray is plotted on the optical layout. The
tabular output of RAY is shown in Figure 6.

RAY AT WAVL 1   (YR,XR) = (.94, 0.00)

SN	Y	X	Z	Y-ANG	X-ANG	OPL
1	4.50000	0.00000	-.71589	6.9864	0.0000	2.58215
2	4.69472	0.00000	-.72694	.3146	0.0000	19.00948
3	4.79909	0.00000	-.21775	-169.9231	180.0000	18.10901
4	1.63055	0.00000	-.04740	-3.4158	0.0000	27.35868
5	.00107	0.00000	0.00000	-3.4158	0.00000	0.00000

Figure 6. A RAY Table for the Powell Maksutov.

PUPIL is used to generate a matrix of rays filling the clear
aperture of the system. The rays are traced as if they came from a
uniformly spaced grid at the object. The ray trace data is internally
stored in FALCON for later use with the spot diagrams, radial energy
curve, and other plotting commands. A table is generated giving the
number of rays traced, the number blocked by apertures, and the number
that failed for other reasons. The physical radius of the exit pupil
is calculated and listed in the table. See Figure 7.

WAVELENGTH UM	NBR RAYS	NBR FAILED	NBR BLOCKED	PERCENT VIGNETTED
.58756	300	0	32	10.67
.48613	300	0	32	10.67
.65627	300	0	32	10.67
TOTAL	900	0	96	10.67

PUPIL RADIUS   1.5916 CM   OPD IN WAVES

FIELD ANGLE   0.00 DG.

FOCUS	YOR	YAV	RMS R	RMS Y	RMS X
0.000000	0.000000	-.000000	.0015058	.0010648	.0010648

WAVEFRONT	RMS	STREHL	XS	YS	FS
	.280	.045			
TILT	.280	.045	0.000000	-.000000	
FOCUS	.207	.186	0.000000	.000000	.710989

Figure 7. PUPIL listing for the Powell Maksutov.

ZPOLY, (Zernike POLYnomial operation), fits a set of Zernike polynomials to the optical path difference data in the ray matrix file generated by the PUPIL command. ZPOLY therefore calculates the geo- metrical approximation to the wavefront at the exit pupil. The poly- nomial data is used to calculate the Strehl ratio. (More about the Strehl ratio in Chapter IV.) See Figure 8.

DISPLA prepares a complete plot of the cross section of the optical layout of all surfaces, excluding the object plane. Dummy surfaces, those with the same index of refraction on both sides would be shown as a dashed line. The scale is automatically set by FALCON. See Figure 9.

--ZPOLY LIST

FIELD ANGLE   0.00 DEG

BI-LATERAL SYMMETRY INVOKED

	TERMS	RMS
	0	.028
TILT	1	.028
FOCUS	2	.020
4TH ORDER	5	.005
6TH ORDER	9	.000
8TH ORDER	14	.000
10TH ORDER	21	.000

STREHL RATIO .985 AT DIFFRACTION FOCUS

FOURTH ORDER ABERRATIONS

MAGNITUDE	ANGLE	DESIGNATION
.000	0.0	TILT
.164		DEFOCUS
.000	0.0	ASTIGMATISM
.000	0.0	COMA
.385		SPHERICAL ABERRATION

RADIAL COEFFICIENTS

ORDER	ZERNIKE	ASPHERIC	RAYS
2	.102	.102	.000203
4	.063	-.296	-.001183
6	.024	.414	.002483
8	.000	.030	.000240
10	.000	.001	.000014
12	.000	.000	.000000

Figure 8. The ZPOLY LIST for the Powell Maksutov.

```
0 SAY 4.500000 SCY 8.50000E+08 1.750000 TH 1.00000E+10
1 CV -6.89600E-02 TH 1.600000 SCHOTT BK6
2 CV -6.44200E-02 TH 18.500000 COBS 1.500000
3 CV -1.88700E-02 TH -18 COBS 1 REFL
4 CV -3.56300E-02 CLAP 1.700000 REFL
5 CV 0. PY
```

4 CM

Figure 9. DISPLA for the Powell Maksutov.
            (Illustration is reduced.) (The listing
            at the top is not a part of the DISPLA
            command.)

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LAYOUT is a more versatile specification than DISPLA. LAYOUT allows for plotting fractional parts of the system and for changing the scale. In addition, when LAYOUT is active, the RAY command draws a ray through the plot rather than creating a table of data. One may use RAY to draw any number of rays through the system at different field angles and wavelengths. LAYOUT may be deactivated by executing the DISPLA command. See Figure 10.
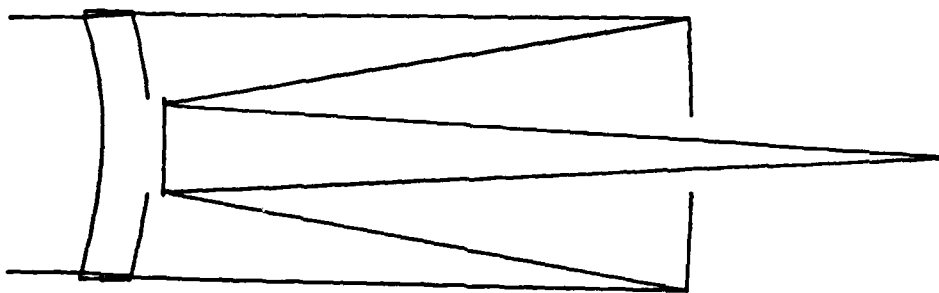

Figure 10. Illustration of the use of LAYOUT.

FANS generates a ray fan and plots the results at the first three wavelengths. A set of rays (called a fan) lying along the tangential plane or the sagittal plane are traced through the system.

A plot is made of the intersection height of the individual rays (relative to the intersection point of the paraxial ray) versus the point of origin at the exit pupil. Figure 11 illustrates the construction of a ray fan and Figure 12 shows the FALCON fan plots. In FALCON, a plot is made at three field angles and at the first three wavelengths. The plot of the sagittal fan is shown only for the positive X-axis as the sagittal function is odd. The tangential fan only is shown at zero field angle because the tangential and sagittal fans are the same for points on axis. Fans are especially useful in systems with higher aberrations because the shape of the fan plot is characteristic of the aberration present (see Lea (20).)
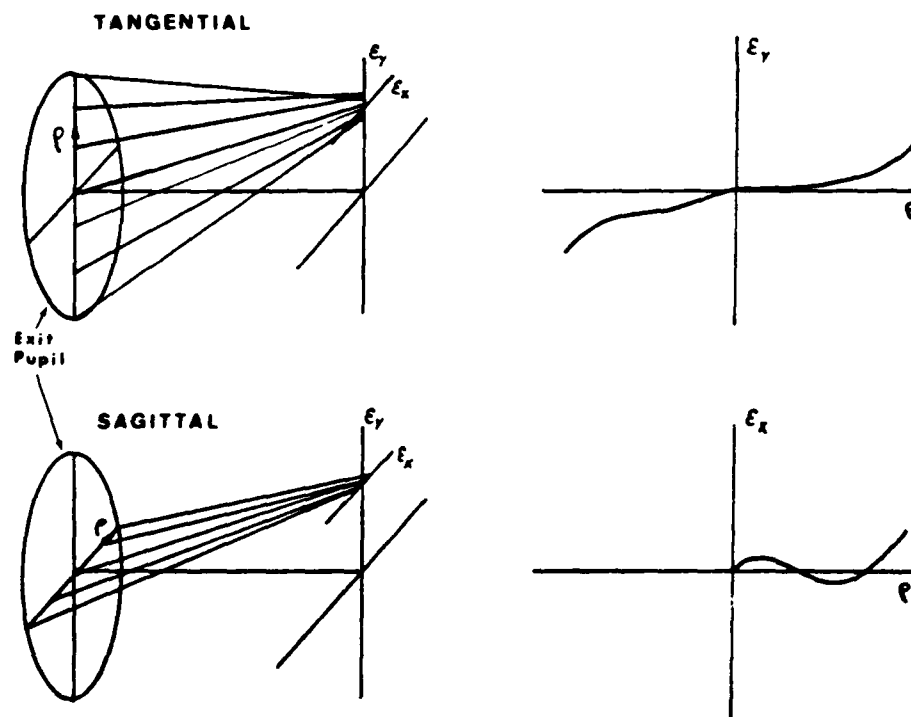

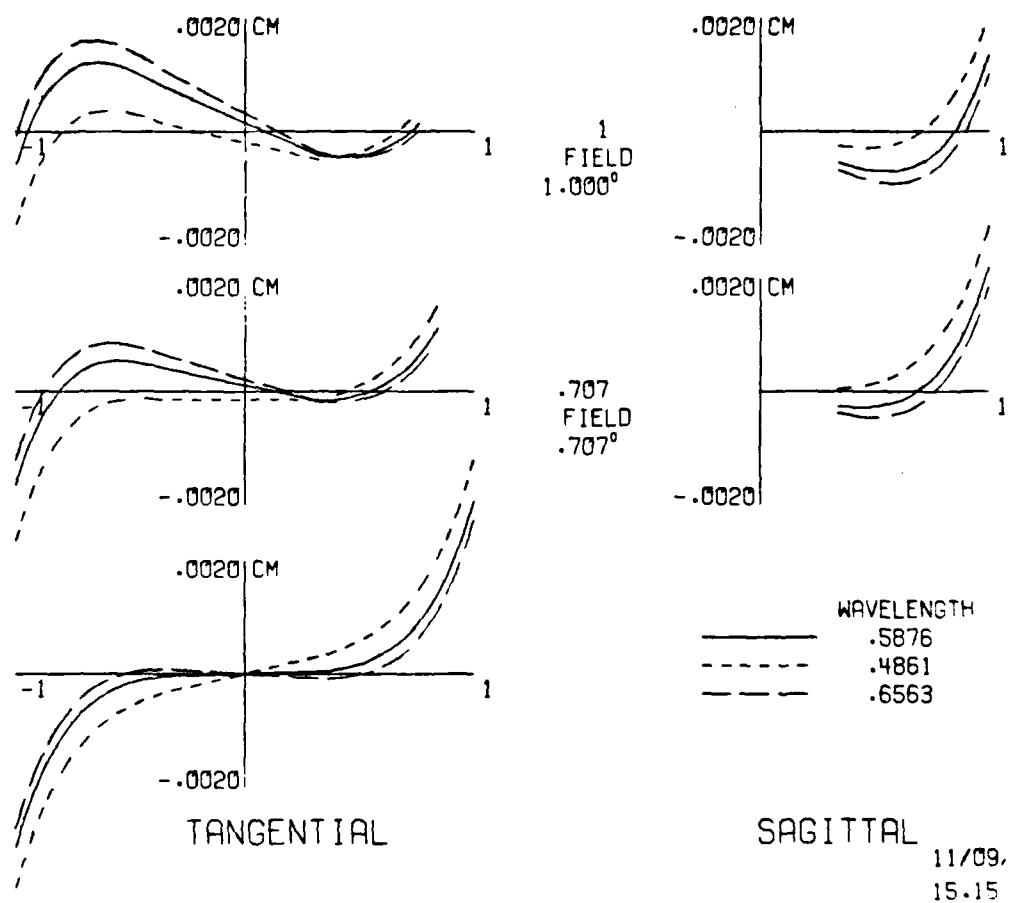Figure 11. Generation of a Ray Fan.

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Figure 12.   FALCON FANS for the Powell Maksutov.

SPOT PLOT is a spot diagram. The ray array formed by the PUPIL command is traced to the image and an XY plot is made of the intersection points of the rays with the paraxial image plane. FALCON uses a different symbol for each wavelength and all five wavelengths can be plotted on the same plot if so desired. See Figure 13.
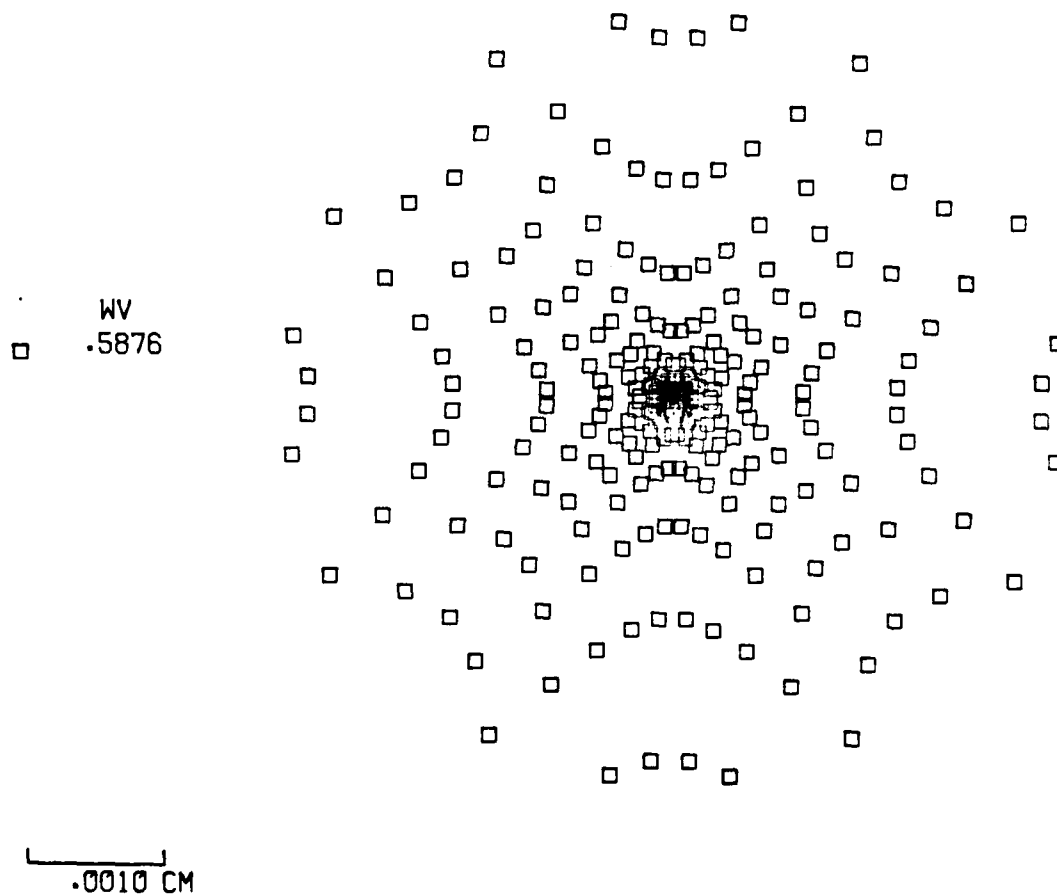
WV
.5876

.0010 CM

Figure 13. SPOT PLOT for the Powell Maksutov.

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SPOT RED, (radial energy plot), is generated from the data of a
SPOT PLOT (although the SPOT PLOT need not be run before the SPOT RED.)
It is a plot of encircled energy versus radius from the centroid of the
spot. An optional table of radii at equal encircled energy or of per-
cent energy at equal increments of radius can be printed. A SPOT RED
is useful for a rapid evaluation of the spot size versus enclosed
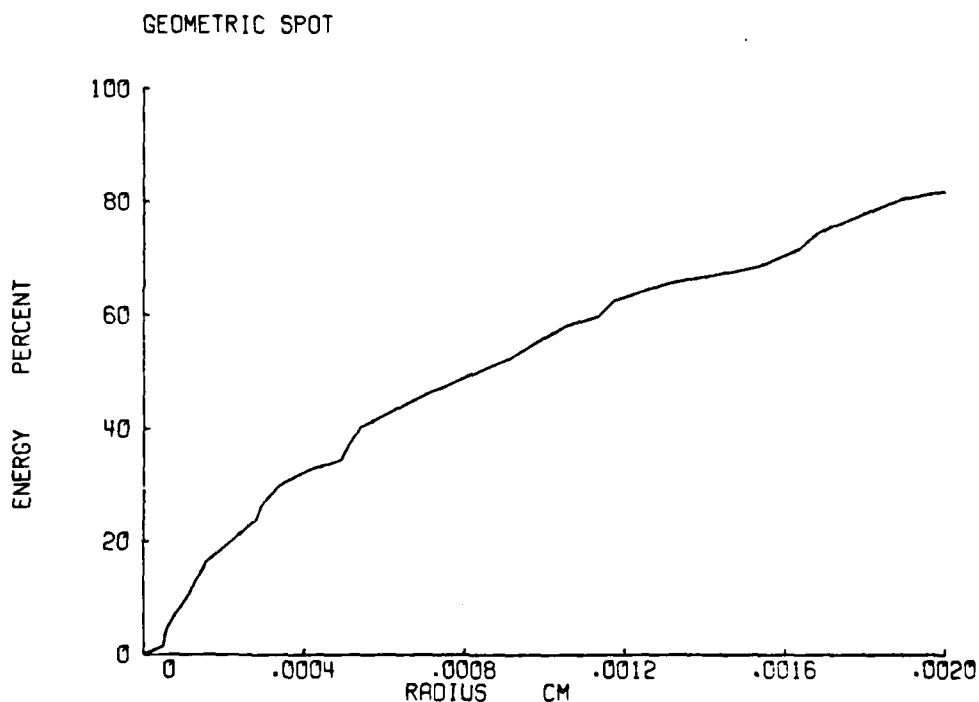energy. See Figure 14.

GEOMETRIC SPOT

Figure 14. SPOT RED for the Powell Maksutov.

Another form of energy plot is a SPOT KED. It is a knife edge energy
distribution, a plot of energy transmitted past the knife edge as a
function of knife edge position. Both plots can be made at any desired

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focus position by adding the term FOCUS X where X is the displacement from the paraxial focal plane.

GOTF is the Geometrical Optical Transfer Function. GOTF is a plot of contrast versus transmitted spacial frequency. The FALCON GOTF is illustrated in Figure 15. More is said about the geometric OTF at the end of Chapter IV.

GEOMETRIC TRANSFER FUNCTION
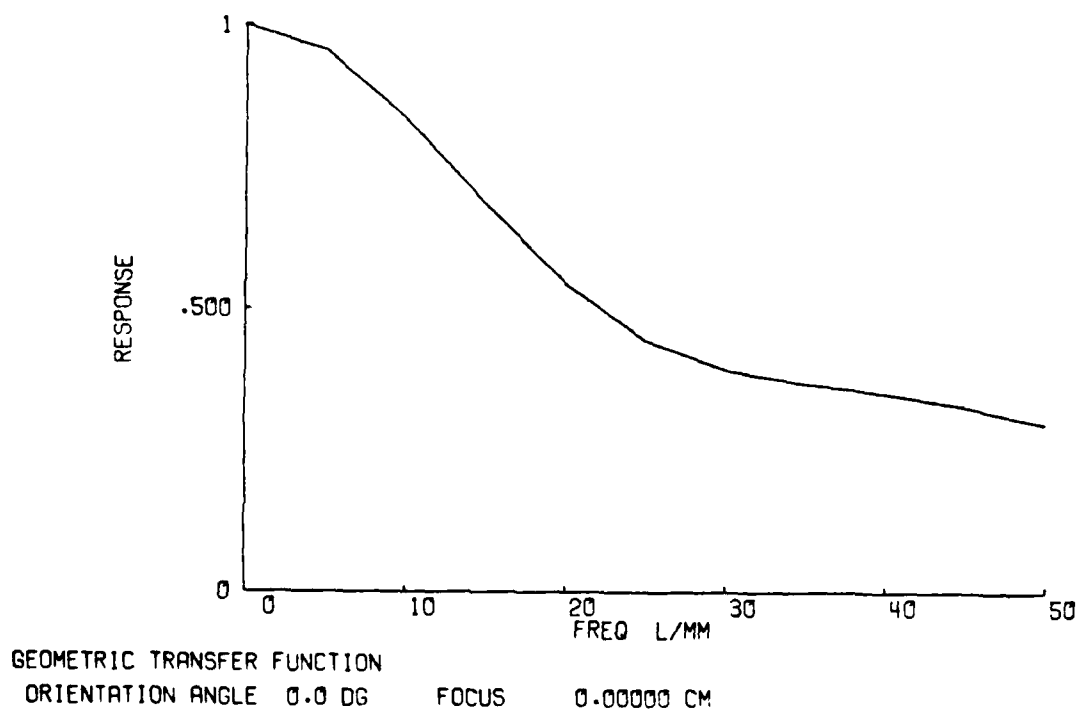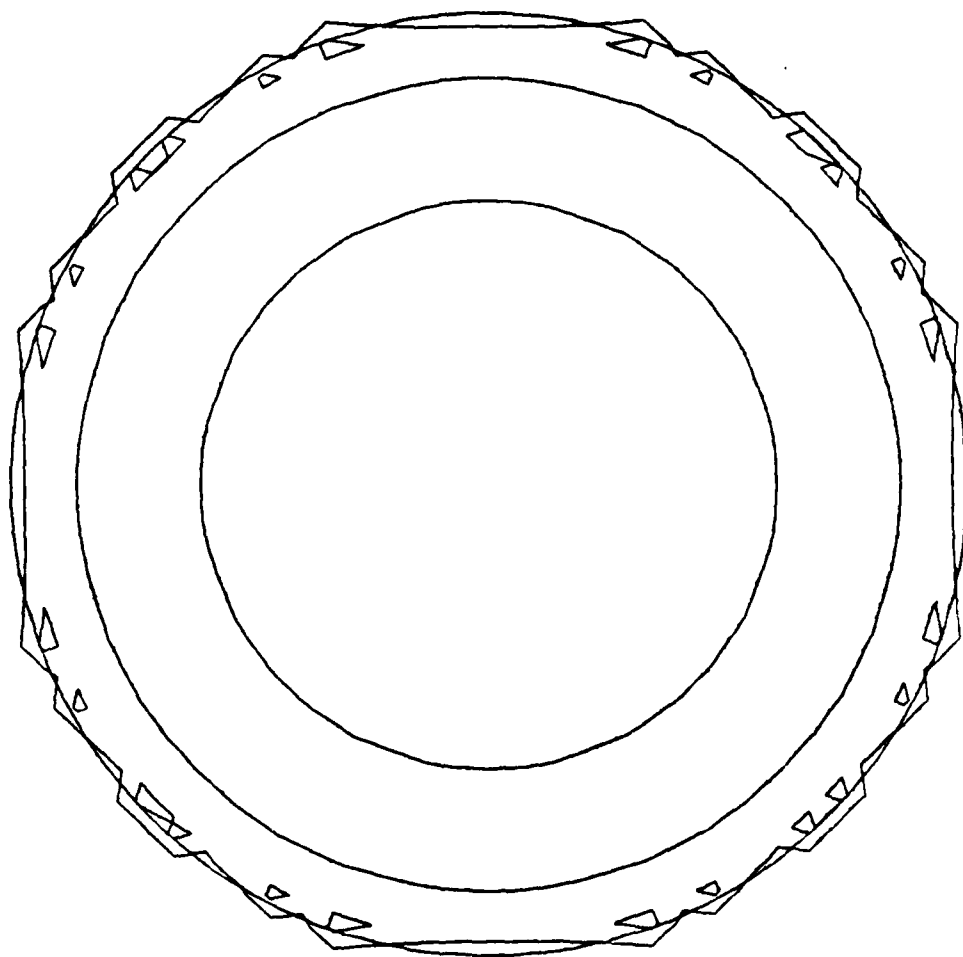ORIENTATION ANGLE 0.0 DG   FOCUS   0.00000 CM

Figure 15.   The Geometric Optical Transfer Function
for the Powell Maksutov.

WAMAP draws a contour plot of the wavefront at the exit pupil. WAMAP uses a set of Zernike polynomials to represent the wavefront. The

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plot is scaled to a fraction of the wavelength in use and can be plotted in any wavelength. The line printer version of the WAMAP provides a symbology so one can tell which contour is at what height. The Tektronix graphics version is a continuous line plot and has no symbology. One must rely on the outer circle of the plot which is taken as zero. The command WAMAP PLOT3D creates both a contour plot and an isometric view of the wavefront. The isometric view gives a three dimensional picture of the WAMAP contour plot and provides easy visual confirmation of the shape of the wavefront. PLOT3D is not available in the line printer graphics mode. See Figures 16 and 17.

It should be pointed out that a complete set of data for the lens under design can be obtained only by running each command in both the line printer mode and the Tektronix graphics mode. This is because most of the tabular data is printed only in the line printer mode and high resolution graphics are available only in the Tektronix mode. Some of the graphics routines generate both a plot and a table of data. When in the Tektronix mode, all plot data is stored in a single permanent file so that each plot can be sent to an off-line plotter (i.e., Calcomp). All plots presented here were made on a Calcomp plotter although some have been reduced for reproduction.

CONTOUR STEP   .200

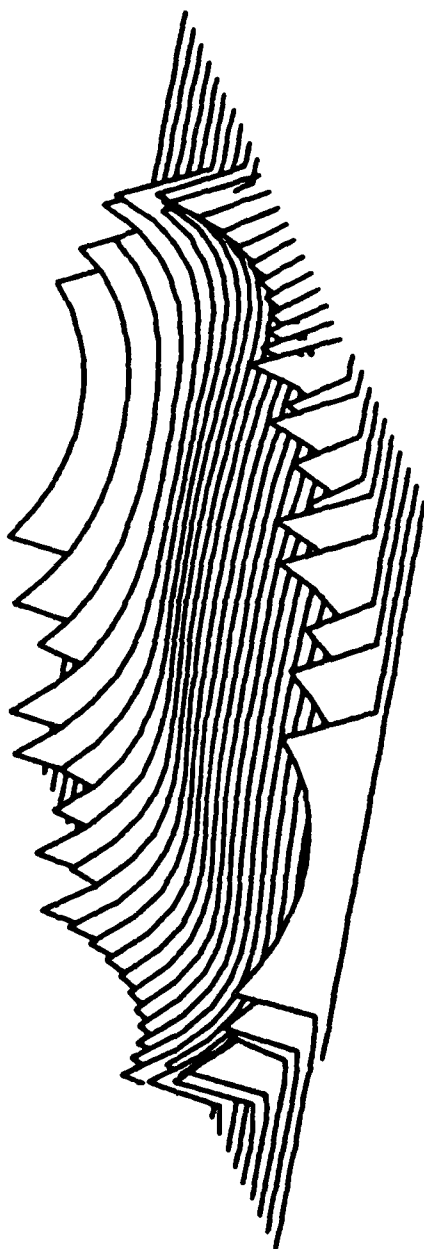Figure 16.   WAMAP Contour Plot for the Povell Maksutov.

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Figure 17. PLOT3D Isometric Plot for the Powell Maksutov.

III. Design Requirements

The Air Force Weapons Laboratory, Kirtland AFB, New Mexico, is studying development of a large Phased Array HEL system (33). Part of the problem includes sampling the beams from each mirror, two at a time, bringing the two beams together through apertures in front of a lens. The resulting interference pattern formed at the focus of the lens can be measured and a determination made as to the relative phase difference between the two beams. A computer program under development at AFWL (7) will be used to identify changes needed in positioning of either mirror to bring the two beams into phase. The requirements on the lens needed to do the job are to be developed here.

AFWL has requested that a standard 3½ inch Questar Maksutov telescope be used as the first element in the lens. (The Questar is a product and trade mark of the Questar Corporation, New Hope, Pennsylvania.) The Questar already has a large enough aperture and will reduce the design problem to that of adding lenses to the focal axis of the telescope to form the desired image. The cost of building a prototype system will be significantly reduced using the Questar since AFWL already has access to one. In addition, the Questar is a high quality, state of the art, telescope possessing on-axis qualities suitable to this problem (i.e., it is diffraction limited on axis).

AFWL has recommended that 2.5cm diameter apertures be used as the entrance apertures to the system and that they be separated by twice their diameter (2d center-center). (The 2d separation was requested, as will be shown later, to provide 5 fringes in the interference

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pattern. It turns out however, that the central obscuration by the secondary mirror in the Questar causes a slight overlap if the apertures are separated by 2d=5cm, see Figure 18. The separation will need to be slightly greater to clear the secondary and will only cause the 5 fringes to be slightly closer together. This will be shown to cause no adverse effects.)
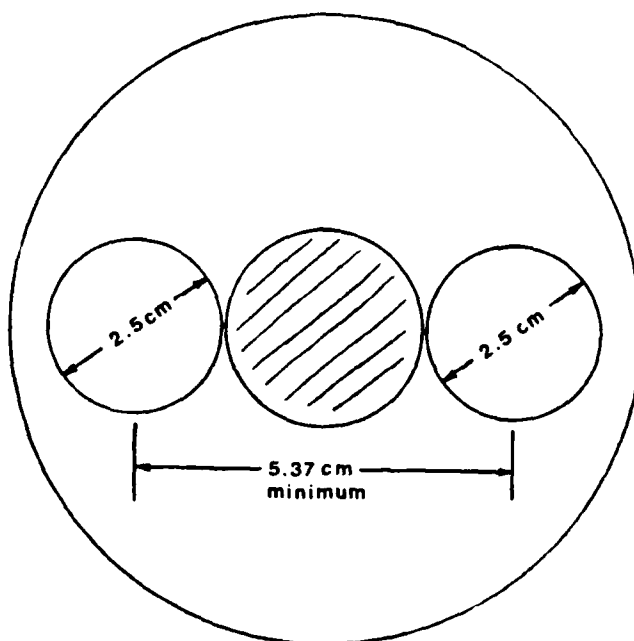

Figure 18. Placement of Apertures over Questar
Corrector Plate.

When two beams are passed through circular apertures separated by a distance h, each forms an Airy disc in the far field (14:329). The two beams interfere where the discs overlap. (The interference of two independent, coherent laser beams can be entirely described by classical diffraction theory (29:290). If the interference pattern

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were large enough, a strip of discrete detectors could be used to measure the intensity profile.

One of the detectors AFWL would like to use is a Fairchild CCD 11. The CCD 11 is a linear strip detector 17μm wide with 256 cells each 13μm long. A coverage of 10 detector cells per interference fringe and a minimum of 5 fringes are needed to provide enough statistical data for the AFWL computer algorithm to measure the profile. Choosing seven fringes as a design start, 10 X 13μm X 7 = 910μm or about 1mm is needed for the diameter of the Airy disc falling on the detector. The focal length of the lens that gives a 1mm Airy disc from a 2.5cm aperture must now be found.

The radius of the first dark ring in the Airy disc is given by (9:352):

$$r = 1.22 \ f\lambda/d$$

where f is the focal length of the lens used to focus the pattern, λ is the wavelength of light, and d is the aperture diameter. Hereafter, the diameter of the Airy disc will be taken as 2r. AFWL is using an argon laser with primary wavelengths of .4765, .4880, .4965, .5015, and .5145μm. The middle wavelength is .4965 and will hereafter be taken as the design wavelength. Taking d as 2.5cm and r as .5mm and solving for f, the required focal length is found to be 20.64m. At the shortest wavelength in question, .4765μm, the required focal length is 20.5m and at the longest, .5145μm, the focal length is 19.9m. Hence, the design focal length will be rounded to 21m, a convenient, arbitrary median.

The number of interference fringes can be approximated as follows: Fringe separation when two beams are passed through apertures of diameter d separated by a distance h (center to center) will be (16:187)

$$\Delta y = \lambda f/h$$

Thus, the number of fringes in the center of the Airy disc is

$$n \approx 2r/\Delta y = (2.44f\lambda/d)/(\lambda f/h) = 2.44\ h/d$$

Rounding n to the nearest integer gives approximately the number of whole fringes in the pattern. One is justified in subtracting one or two from n since the fringes nearest the dark ring that defines the edge of the Airy disc central bright spot might be of very low intensity or not visible at all. Comparison with the experimental results of Thompson and Wolf (32:898-900) indicates at low ratios of h/d, where $1.6 \le h/d \le 3.2$ the predicted number of fringes is very good, see Figure 19.

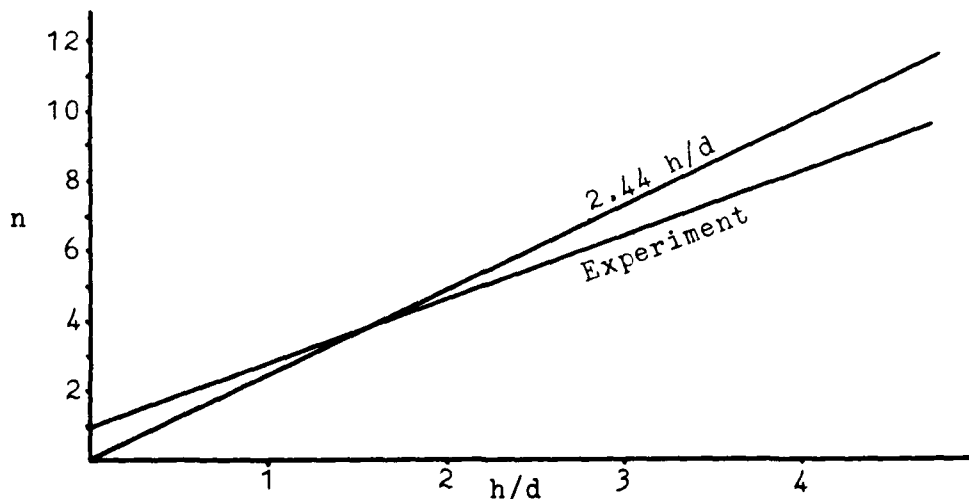Figure 19. Comparison of Predicted Number of Fringes with Experimental Results of Thompson & Wolf.

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Apertures of d = 2.5cm separated by 2d and f = 2100cm give
n = 5, the minimum number of fringes needed. A separation of 2d = 5cm,
however, overlaps the secondary mirror of the Questar. The minimum
separation without overlap is 5.37cm, see Figure 1, and gives n = 5.24 = 5
so that the 5 fringes are only slightly closer together. At f = 2100cm
the Airy disc diameter is at or exceeds 1mm for all wavelengths and
the decreased fringe separation will cause no problem as each fringe
will cover at least 15 detectors.

The Questar, focused at infinity, has a focal length of 127cm.
The requirement is to add the necessary lenses to the back of the
Questar to yield an effective focal length (EFL) of 2100cm and keep the
overall length (from the front of the lens to the focal point) to about
46cm. The problem is now one of optical design. The next chapter will
discuss the relationship between design by geometric optics techniques
and the diffraction effects that are to be observed. Chapter V will
cover the design and optimization of the lens.

IV. Design by Geometric Optics vs Diffraction Effects

An optical system free of aberrations in the image is said to be a perfect system or a perfect lens. If a point object is imaged by a perfect lens the image is not a point but, rather, a complex diffraction figure described by the point spread function (PSF). The form of the PSF depends on the shape of the exit pupil of the system (33:204). (The point spread function is the mathematical form of the intensity distribution in the image and is dependent on the aperture of the imaging system, its aberrations and the effects of diffraction (1:7).) When the exit pupil is circular, the diffraction figure is the Airy pattern, the intensity of which is governed by the first order Bessel function $J_1(v)$ (2:396):

$$I(r) = \left(\frac{2J_1(v)}{v}\right)^2 \quad \text{where } v = \frac{2\pi nar}{\lambda R}$$

In the equation, r is the radial distance from the center of the pattern, n is the refractive index, a is the radius of the exit pupil, R is the radius of the reference sphere (i.e., the radius of the sphere converging to the image from the exit pupil), and λ is the wavelength of the light. The equation is normalized so that the intensity of the center of the pattern is one (see Figure 20).

Very small amounts of aberration will cause insignificant changes in the intensity profile of Figure 3 (12:3). Large amounts of aberration tend to distort the profile such that the Airy pattern is no longer the cominant form of the PSF. Small aberrations are taken as
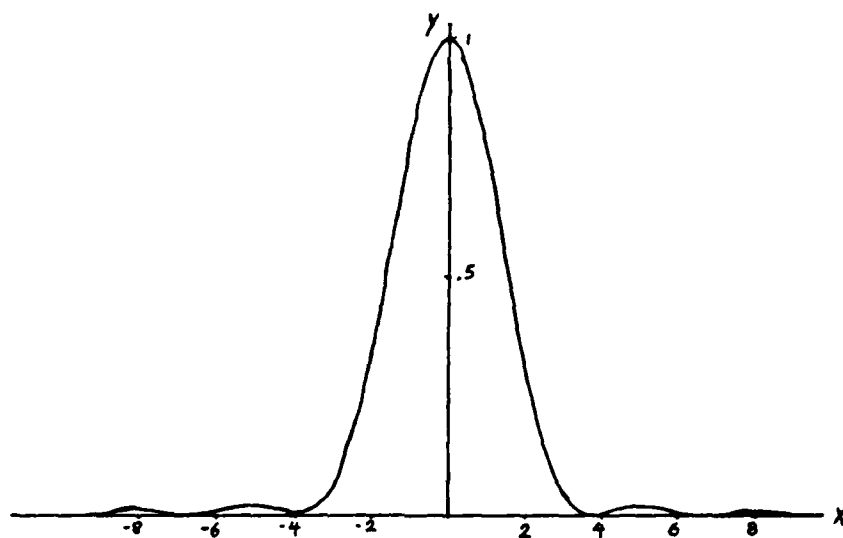
34

Figure 20. The Airy Pattern (Fraunhofer Diffraction
of a Circular Aperture)

Plotted is $y = \left(\dfrac{2J_1(x)}{x}\right)^2$

those which cause a deformation of the wavefront of less than one or
two wavelengths (31:290). Discussions on imaging are usually divided
into two areas: (1) when the effects of aberrations are small and the
imaging must be spoken of in terms of diffraction effects, and (2) when
the aberrations are large and the imaging can be treated by geometrical
optics (31:290). Geometric optics give a valid description of image
formation so long as the results are taken from regions of the light
beam which are not very near to focus, and also not very close to the
edge of a beam of limited aperture (12:2). Within the validity of
geometrical optics, it is found that each ray can be looked upon as the
path followed by the corresponding element of wavefront (12:3).

When aberrations are gradually introduced to a perfect diffraction pattern from a circular aperture, it is found that the effects on the PSF are much the same for any combination of aberrations. The effect is that the intensity in the central peak decreases, the half-width of the central peak does not change and more light ends up in the outer rings (33:206). If the quantity given by

$$1 - \frac{4\pi^2}{\lambda^2} \left[\frac{\iint (W(x,y))^2 dxdy}{A} - \left(\frac{\iint W(x,y) dxdy}{A} \right)^2 \right]$$

is less than 0.8, the change in the diffraction pattern is just detectable. In the equation, A is the area of the exit pupil and $W(x,y)$ is the total wavefront aberration, the OPD between a point on the wavefront and the reference sphere. Integration is taken over the area of the exit pupil. This is the Strehl ratio first developed by K. Strehl in the late 19th century (12:3). The square brackets enclosing the integrals form the total variance of the wavefront aberration (27:59). The value of 0.8 is the generally accepted lower limit for a diffraction limited Strehl ratio and is based on the Rayleigh $\frac{1}{4}\lambda$ criteria for wavefront distortion (33:206).

The immediate question arises of how is the quality of the diffraction pattern to be predicted when geometric optics techniques do not predict diffraction effects? FALCON can provide all the classic geometric techniques, ray tracing, spot diagrams, radial energy distributions, ray fans, geometric optical transfer function, aberration tables as well as wavefront contour plots, all of which are useful for one purpose or another. But this geometrically derived data cannot be

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assumed valid for the prediction of imaging down to the diffraction level.

All is not lost, however. In 1929, A. E. Conrady (4; 5) published two books in which he developed the theory and application of aberrations and physical optics. In his second book, he proves the wavefront aberration can be calculated from the geometrically derived optical path difference along the rays (5:XII). In addition, according to Palmer (27:62), Hopkins has shown that the Strehl ratio can be calculated from ray trace data. In FALCON, the command ZPOLY LIST fits a set of Zernike polynomials to the ray trace data previously calculated, thus representing the wavefront by a set of polynomials and calculates the Strehl ratio at the diffraction focus. (Zernike polynomials are discussed briefly in the FALCON users manual (21) and in more detail in Born and Wolf (2).) The Strehl ratio can thus be found at any stage in a design problem using FALCON.

It has already been mentioned that when the aberrations are small the distribution of intensity in the Airy disc is changed but the halfwidth is not affected. Therefore, if the Airy disc were suffering from only a small amount of aberration, the interference pattern we are trying to see will suffer only a small decrease in visibility. Lasers typically have long coherence lengths many times longer than incoherent or partially coherent sources and high monochromacity at each wavelength. Thus, the visibility of the fringes will be less affected by small aberrations than one finds using partially coherent sources. (The visibility of fringes is directly related to the degree of coherence (32). As such, the high degree of coherence will aid in this problem

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by guaranteeing that when a system is designed with a suitably high Strehl ratio, the fringes will have high visibility.)

Another measure of the imaging capabilities of a system not yet metnioned is the Optical Transfer Function (OTF). Quite good descriptions of the OTF can be found in various sources (11:2-11; 31:308-324; 33:212-220; 27:63-90; 1). Most of the larger optical design computer programs can calculate the OTF or at least the geometrical approximation to it and many programs have been written exclusively to calculate the OTF (23:45-48; 17:14-20; 18:49-52). The OTF is a good indicator of image quality but is generally more applicable in the region where the aberrations are large enough that the diffraction image of a point source no longer has the pronounced Airy pattern (11:2) and where the aberrations are not so large that geometric optics is adequate to assess the image (33:212). Palmer (27:63) points out that the OTF is more suitable for systems with extended image fields and should be applied to optical systems where the diffraction limit is not a design criteria.

The OTF can predict the image quality of a near diffraction limited system provided the OTF is calculated by diffraction techniques. In the geometric approximation, the OTF function is expanded and only the wavelength independent terms are retained (27:71-72). The geometric OTF disagrees with the diffraction OTF when the aberrations are very small and so the geometric OTF is of little value for highly corrected systems (18:51; 31:230). The geometric OTF is found in many programs because of its simplicity of calculation and because it requires significantly less computer time than does the diffraction OTF.

FALCON can calculate only the geometrical OTF and, as such, the OTF
will not be of any use in this design project.

V. The Design

The requirements for this design were developed in Chapter III. The requirements are to develop a lens 2100cm in focal length such that when two apertures of diameter 2.5cm separated by just over 5cm are placed in front of the first element, the Airy diffraction pattern formed by each aperture will be 1mm in diameter. The aberrations in the lens must be low enough that the Airy patterns are well formed and a good intereference pattern can be established. This leads to the requirement that the lens system have a Strehl ratio exceeding 0.8, the accepted minimum Strehl ratio for a diffraction limited system.

The lens is to be designed in air and the index of refraction of air is to be taken as 1.00. The index of refraction of each glass element, then, is to be measured relative to air. The lens will not be designed to the standard visual lines of C and F (hydrogen) and d (helium) (20:73) rather, will be designed to the five primary wavelengths of the argon laser. The wavelengths are: .5145, .4965, .5015, .4880, and .4765µm. The center wavelength is .4965 which will be the design wavelength and for chromatic correction the extremes of .5145 and .4765µm will be used.

This design is not unlike designing a Barlow lens for an astronomical telescope (8:277). This problem differs in two ways. First, a Barlow usually doubles or at most triples the focal length of the telescope. Here, the focal length is to be about 16 times longer. Second, a Barlow is usually a cemented doublet to correct for wavelengths detectable by the eye. In this design, the elements will be

kept separate partly because the power to be transmitted is not known
and since the cones of laser radiation will be focused to very small
diameters the power could become important. Cemented lenses have been
known to crack or become separated under laser illumination due to
absorption of energy by the cement. In addition, separate elements
adds to the number of variables that can be changed which will aid in
the design process.

The two elements in a Barlow are a flint and a crown. The flint
is usually placed on the side facing the objective to permit the use of
shallower curves (8:280). This is probably due to industry inertia
rather than a design requirement. Barlows were made by hand and eye
decades ago and shallower curves were easier to make. Shallow curves
introduce less aberration and in the early days of Barlow design there
were few ways to reduce aberrations so the curves were kept shallow.
The flint does not have to be on the objective side, achromats can be
made in either configuration, (see Hecht and Zajac for example (9:191)).
To that end, this design will not be restricted to a particular orien-
tation. The results of a change of glass or orientation is available
so quickly using FALCON that it would be counterproductive to restrict
the design to any particular arrangement.

One way to develop the design would be to use commercially
available lenses from one or more of the optical supply houses. A quick
check of several companies, notably Oriel, Ealing, and Melles Griot
shows that the lenses available are generally designed for simple
applications such as college physics labs and are not available in a
wide variety of glass types. Melles Griot (26) has the largest

selection of small lenses of various curvatures but they, also, are found only in a narrow range of glass types (Schott BK7 and in a few lenses, LaSF9). Thus, the use of commercial lenses would not be likely to produce useful results. Even if the lenses were available, the number of variables for design changes would be seriously reduced and it would be very difficult to reduce aberrations and correct for chromatic errors. The lens designed here will therefore require the manufacture of the individual elements excluding, of course, the Questar.

One lens added to the Questar would certainly be capable of extending the focal length to 2100cm but would, no doubt, create unacceptably large chromatic problems. (A brief example of a single lens solution to this problem will be given later.) Achromatic lenses must be made using three elements to correct both axial and lateral color simultaneously (20:78). In this case, the narrow cones will keep the lateral color small when the axial color is reduced so two lenses should be satisfactory. (The cone of focus will be quite small in diameter (about 1mm at the exit pupil) yet very long, about 20cm. If the axial color is made small, the lateral color will be very much smaller since the angles of convergence are so close to zero.) One also does not want to make the number of variables unmanageably large. Three lenses would introduce no less than 15 variables. Two lenses will have 10. Finally, from a manufacturing point of view, two lenses will be less expensive to procure than three.

Prior to manipulating lenses in the focal cone of the Questar, the Questar must be modeled on FALCON. The Questar is a 3½ inch

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Maksutov telescope sometimes called a Maksutov-Cassegrain. (The

Maksutov is actually a modification of the Schmidt telescope combined

with a Cassegrain design. The Schmidt has a spherical primary, where

the Cassegrain has a paraboloidal primary. The Maksutov retains the

spherical primary but uses a different corrector plate. Its corrector

is a weakly negative meniscus lens. The Schmidt corrector is a thin,

aspherical, almost plane-parallel plate. The Maksutov is Cassegrain-

like because the focal cone goes through a hole in the primary and

focuses outside the telescope, (see Figure 9). The Schmidt focuses

inside the telescope and there is no secondary or hole in the primary.)

In the Questar, the secondary is an aluminized spot on the inside sur-

face of the corrector plate. Therefore, the secondary is of spherical

shape, and thus, every optic in the Questar is a sphere.

The Questar telescope is a highly corrected, diffraction

limited system. In the interest of protecting the Questar design, the

parameters of the optical elements are confidential to the Questar

Corporation. The President of Questar, Dr. Douglas Knight, was kind

enough to release the data for the purposes of this project. The

proprietary rights to the data will be respected and the information

will not be presented here in any form.

Spherical aberration in the Questar is controlled by a very

slight aspherizing on the first surface of the corrector plate.

FALCON allows for aspheric surfaces and it was a simple task to add the

required aspheric coefficients to the corrector plate curvature in the

model to bring all the primary aberrations on axis (and out to .75

degree, the semi-field angle of the Questar) to zero. Since the Questar

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was designed as a visual optical instrument, the model wavelengths used
were the standard design wavelengths (see page 9, Chapter II).

The diffraction limit at .58756μm for the Questar predicts an
Airy pattern diameter at the 127cm focus of .02mm. The geometric spot
diameter found by FALCON is .0076mm. The Strehl ratio at this wave-
length is .997 and is an indication of the superb imaging for which
the Questar was designed. Since there is only one refractive element,
and it is a weakly negative lens, the chromatic aberration at the focus
is quite low: a PAC of .000786cm and PLC of .000621cm. A ray fan is
illustrated in Figure 21 on axis at the three design wavelengths. Note
the focus error for each wavelength is below one wavelength OPD. The
Questar wavefront contour and isometric plot are shown in Figures 22 and
23. The wavefront is flat to well within a quarter wave, exceeding the
Rayleigh ¼λ criteria (33:207).

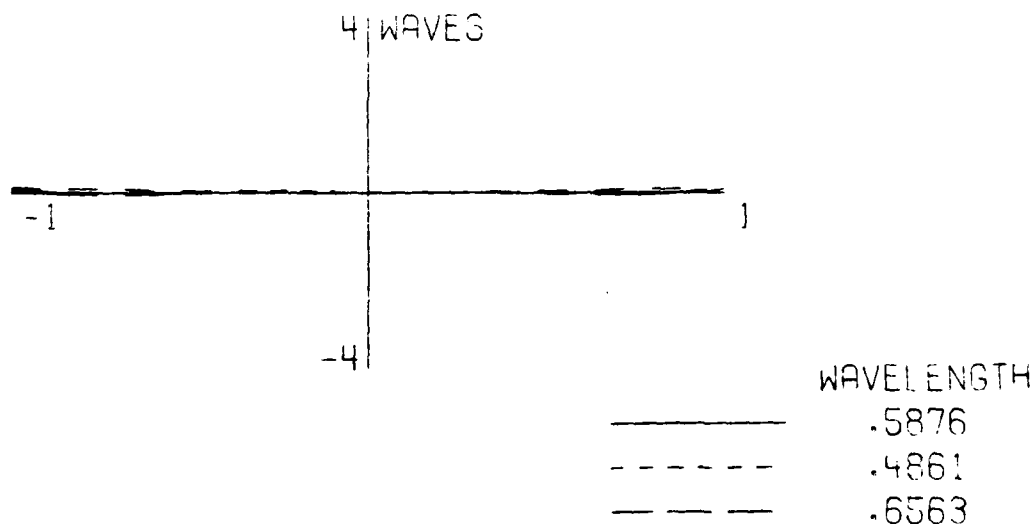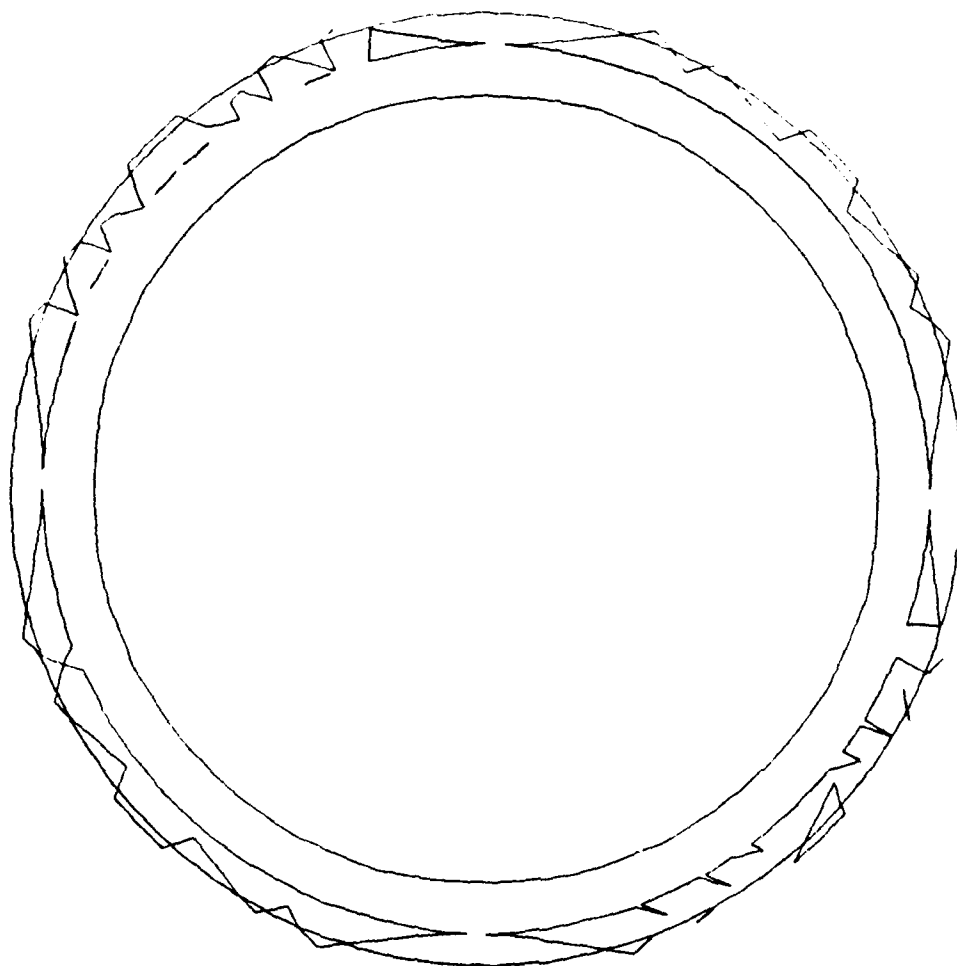|	WAVELENGTH
————	.5876
- - - - - -	.4861
— — —	.6563

Figure 21. On Axis Fan in OPD Measure for the
Questar Model.

CONTOUR STEP   .020

Figure 22.   Wavefront Contour Plot of the Questar
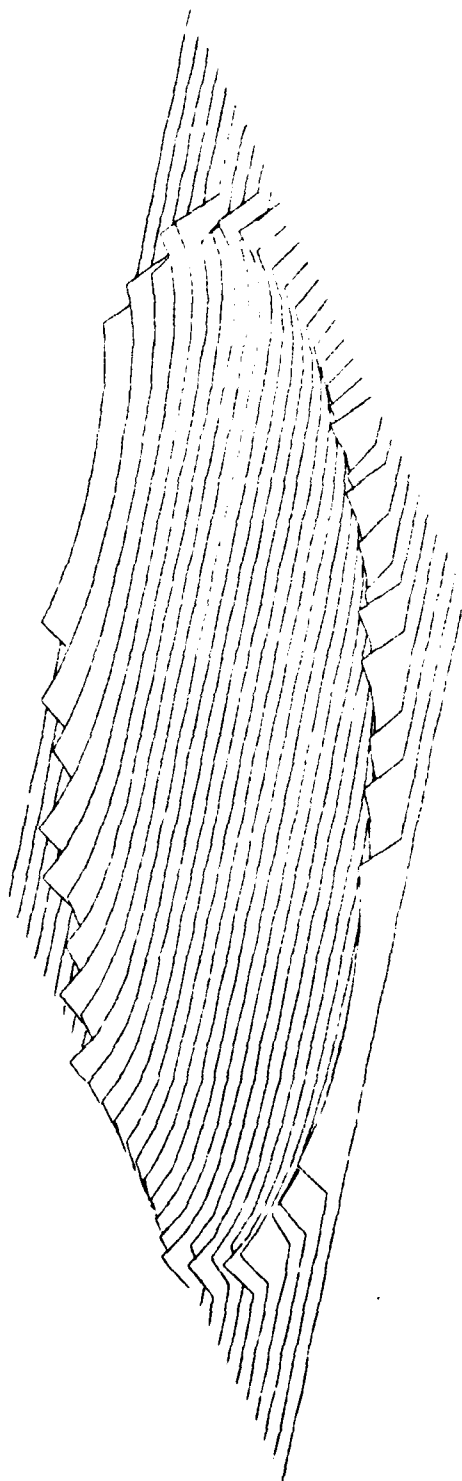at .58756µm.

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Figure 23. Isometric Plot of the Wavefront of Figure 22.

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The Questar focuses by sliding the primary forward and backward on a light baffle. The focusing is controlled by a screw protruding from the back of the primary mount and control box (see Figure 24). The screw has 32 threads per inch allowing for a .7937mm motion of the primary with one full turn of the screw. In the model, focusing is simulated by changing the distance between the primary and the secondary. For this design, that distance is set such that the effective focal length is 127.0598cm, the infinity focus of the Questar. The distance from the secondary to the paraxial focus is then 28.0705cm.
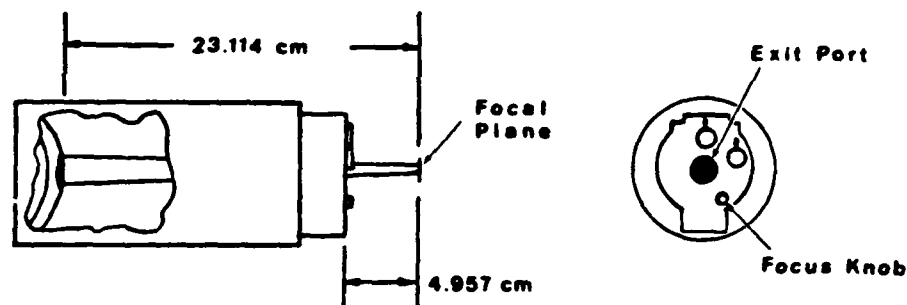

Figure 24. Questar Back Focus and Control Box.

The light baffle is hollow and its interior could be used for placement of lenses; however, placement of a single lens inside the baffle closer to the secondary will introduce large chromatic aberration (ChA) at the next lens. To control the ChA, the lens inside the baffle would have to be an achromatic lens and a second achromatic lens

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some distance away would be needed. Then, four lenses have been used
and the problem has been solved with more lenses than necessary.
Therefore, this design will be made with two lenses outside the control
box.

At this point, it is instructive to present the results of a
single lens solution to the problem. Carefully defining the lens deck
so that FALCON does most of the work, the solution will come out such
that the curvatures on each surface will not be too steep. One can
expect that SA can be made relatively small and since we are working
on axis, the remaining Seidel aberrations will come out small. In addi-
tion, the PAC will be small although by no means zero. The PLC on the
other hand will most likely be very bad. At such small angles, the
colors can cross the axis at very different points and still be very
close to each other in terms of transverse measure. Even the Strehl
ratio can be fairly high for such a lens for the LChA will not seriously
affect it. For this application, however, a high Strehl ratio and a
near zero LChA is needed.

The FALCON lens deck for the single lens looks like:

```
0 SAY 4.47 YFANG .1 WV .4965 .5145 .4765 .5015 .4880
1
2
3
4                    PY .06
5 CV 0 CLAP .25 TH .5
6 SPY .04 CLAP .25 TH .2 SCHOTT BK6
7 PUY -2.128E-03 CLAP .25
8 CV 0 PY
9 END
```

The terms on each line are described in Chapter II. Lines 1-4 are
blanked because the Questar data is listed there. The PY .06 in line 4
was arrived at experimentally and causes the distance to the first
surface of the lens to be set so that the curvatures calculated in
lines 6 and 7 do not come out too large. The paraxial solves are in
lines 6 and 7 to set the back focus and effective focal length to about
18cm and 2100cm respectively. The last curve, line 8, tells FALCON to
position curve 8 at the location of the exit pupil. If curve 8 were
not there, the exit pupil would default to the last surface (curve 7)
and an erroneous pupil diameter would result. PY without a numerical
value defaults to 0.0 and instructs FALCON to locate the image plane
(since the axial ray crosses the optic axis at the paraxial image
location). The results of this design are listed below:

```
EFL: 2100.5176 cm, BF: 18.7970 cm, Length: 27.927 cm
Distance from Questar secondary to lens: 26.377 cm
Curvature of surface 7: -.731433 cm⁻¹(-1.36718 cm radius)
Curvature of surface 8:  .764931 cm⁻¹(1.30731 cm radius)
Location of exit pupil: 1.231634 cm left of curve 7 vertex.
Aberrations: SA3  -.004391, CMA3  -.000354,
             AST3  .000133, DIS3  .000155,
             PTZ3  .000053, PAC  .006868
             (units cm)
BF at .4965  m:  18.79699 cm
BF at .4675  m:  20.7487 cm
BF at .5145  m:  17.4510 cm
Pupil radius: .0421 cm
Strehl ratio: .862
```

The aberrations are not too bad; spherical aberration could
probably be reduced by bending the lens (i.e., removing the paraxial
solves in lines 6 and 7 and making equal but opposite changes in the
two curves maintaining the power of the lens). This would not, however,
reduce the LChA. The magnitude of the LChA is seen to be large from the

difference in BF of the .5145μm ray and the .4765μm ray. The LChA is

3.298cm! The Strehl ratio is above .8 (the limiting factor recommended

by Strehl) but could be improved. (This design could be improved but

the bad LChA cannot; therefore, it would be pointless to continue this

design.) The only way to correct the LChA is to have two lenses added

to the focal cone.

The design of a two lens system starts by changing the lens deck

to accommodate two more curves. The lens deck now becomes:

```
0 SAY 4.47 YFANG .1 WV .4965 .5145 .4765 .5015 .4880
1
2
3
4               TH 25.8
5 CV 0 CLAP .25 TH .5
6 CV 0 TH .2 CLAP .25 SCHOTT F10
7 CV 0 TH .2 CLAP PICKUP 6
8 SPY 3.83E-02 CLAP .25 TH .2 SCHOTT BK6
9 PUY -2.128E-03 CLAP PICKUP 8
10 CV 0 PY
11 END
```

where lines 6 and 7 make up the first lens and 8 and 9 the second.

Editing in a non-zero curve on lines 6 and 7 of .5 and -.6 respectively,

the FORD aberration list gives the following results: SA3 .007825,

CMA3 .007172, AST3 .000493, DIS3 .000102, PTZ3 .000022, and PAC .001014.

Again, a small field angle is allowed which accounts for the non-zero

coma, astigmatism, distortion, and field curvature. These values are

not bothersome because they will become very much smaller as the lens

is improved and will be zero on axis.

Bending the first lens and watching the SA3 change allows the

spherical aberration to be iteratively reduced to zero. In the process

the PAC changes from positive to negative. This suggests the difference

in dispersion of the two glasses, F10 and BK6 is not high enough.

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Changing the flint component and iteratively reducing the SA3 to zero

with each glass change brings the PAC up to a value near zero. The best

glass, chosen somewhat subjectively, was BASF53. When the SA3 is

brought to zero using BASF53 the PAC is -.000233.

The PAC can now be further reduced by making slight changes in

only one curve, say curve 7, then bending the lens to zero the SA3

again. One observes the change in PAC at zero SA3. If it is better,

the surface (i.e., curve 7) can be changed slightly more in the same

direction and the process repeated. If it is worse, the surface must

be changed in the opposite direction. In this manner, the SA3 and PAC

are made simultaneously zero in about 10-15 cycles (where a cycle

includes 10-20 iterations to reduce the SA3). (This task would be

virtually impossible to do in the batch mode. In the FALCON interactive

mode, however, the process takes about 90 minutes depending on how

shrewd a guesser you are.)

Nothing has been mentioned up to this point about what was

happening to surfaces 8 and 9. They are controlled by paraxial solves

rather than fixed curvatures so that every change (i.e., a change in

curve 7) has resulted in a change of both curve 8 and 9. Thus, a manual

change in a single parameter is really a change in three parameters.

This is no problem since the aberration table is computed for the entire

system (the Seidel aberrations are the sums of aberration contributions

of each surface (19:205)). Curves 8 and 9 were observed at several

points during the iterative procedure to ensure they were not growing

to unrealistic values. (A somewhat arbitrary value was chosen as the

limit that would be allowed on a curve. The largest curve found on a

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.5cm diameter lens in the 1981 Melles Griot catalog is about 1.89cm^{-1}.

At one point, curve 8 was found to be large and growing. It had reached 3cm^{-1} when a review of the PARAX list for .4965μm showed the angle of the ray after refraction through surface 8 was somewhat steeper than it had to be. A little juggling of the TH in line 7 (distance between curves 7 and 8) and the TH in line 8 (thickness of lens) markedly reduced the angle. The final values obtained are listed below:

```
0 SAY 4.47 YFANG .1 WV .4965 .5145 .4765 .5015 .4880
1
2
3
4               TH 25.8
5 CV 0 CLAP .25 TH .5
6 CV .36140 TH .2 CLAP .25 SCHOTT BASF53
7 CV -.61035 TH .1 CLAP PICKUP 6
8 SPY 3.83E-02 CLAP .25 TH .4 SCHOTT BK6
9 PUY -2.128E-03 CLAP PICKUP 8
10 CV 0 PY
11 END
```

This system has an EFL of 2100.5235cm, BF 17.9982cm F/# 234.96, Length 27.85cm (overall length front of Questar to focus, 45.85cm). Curve 8 came out -1.423342cm^{-1} and curve 9 1.883775cm^{-1}. The location of the exit pupil is -.983673cm (0.9837cm left of surface 9). A LAYOUT of the final design is shown in Figure 25. Note, surface 5, the stop, is 2.686cm outside the control box (see Figure 24).

The resulting aberrations: SA3 0.000000, CMA3 .00028, AST3 .000262, DIS3 .000076, PTZ3 .000021, and PAC 0.000000, are much better than those that would have been obtained with a single lens. The PAC is zero only to six decimal places. This is clear from the fact that the LChA is not zero. From the PARAX at wavelengths .4765 and .5145 μm, the BF difference (i.e., the LChA) is .00876cm (compare
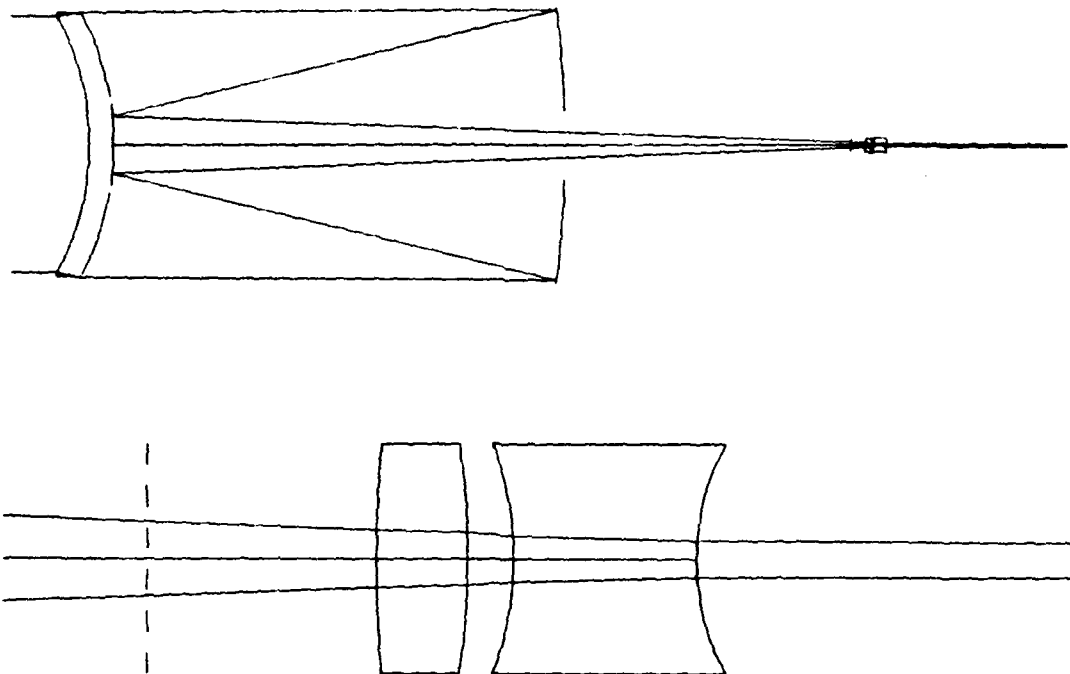
Figure 25. LAYOUT with Enlarged Detail of Added Lenses.

this result with the LChA for the single lens, 3.298cm). Thus, the five
primary wavelengths have been brought to a focus within a .0543cm
region.

The pupil radius comes out to .0396cm and the root mean square
spot diameter is .007038cm. (The RMS spot size as caluclated by FALCON
would be more useful with a lens design where the image is far from the
diffraction limit. Here it is useful only as a standard measure of
spot size to compare spots at different wavelengths or to check for
improvement. In this design, recall that diffraction predicts a spot
size of about .1cm and the geometric value of .007038cm serves only to

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show that the design may be diffraction limited.) The SPOT PLOT at
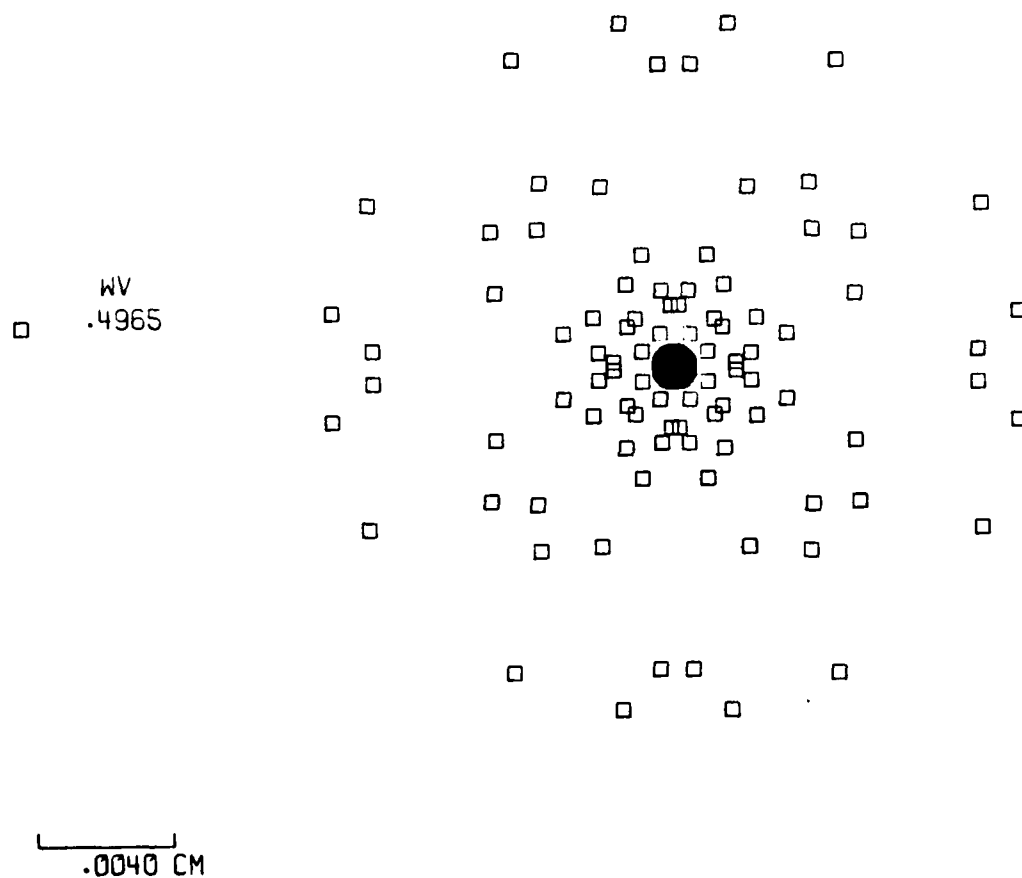.4965 µm is shown in Figure 26.

WV
.4965

└─────────────┘
.0040 CM

Figure 26.   Spot Diagram at .4965 µm for the Design.

From an ESCAN list (i.e., SPOT PLOT ESCAN LIST), 100% of the transmitted
energy is found to lie inside a circle of radius .01cm. The radial

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energy distribution curve (SPOT RED) is shown in Figure 27. Hopkins (12:16-17) warns that it is impossible to interpret geometrically produced spot diagrams (or radial energy curves) in any precise way. He points out, for example, if the wavefront turns in rapidly at the edge of the pupil, the spot diagram may end up with a denser central cluster of spots. There is no way to determine a "weight" to apply to parts of the diagram to redistribute the point spread function.
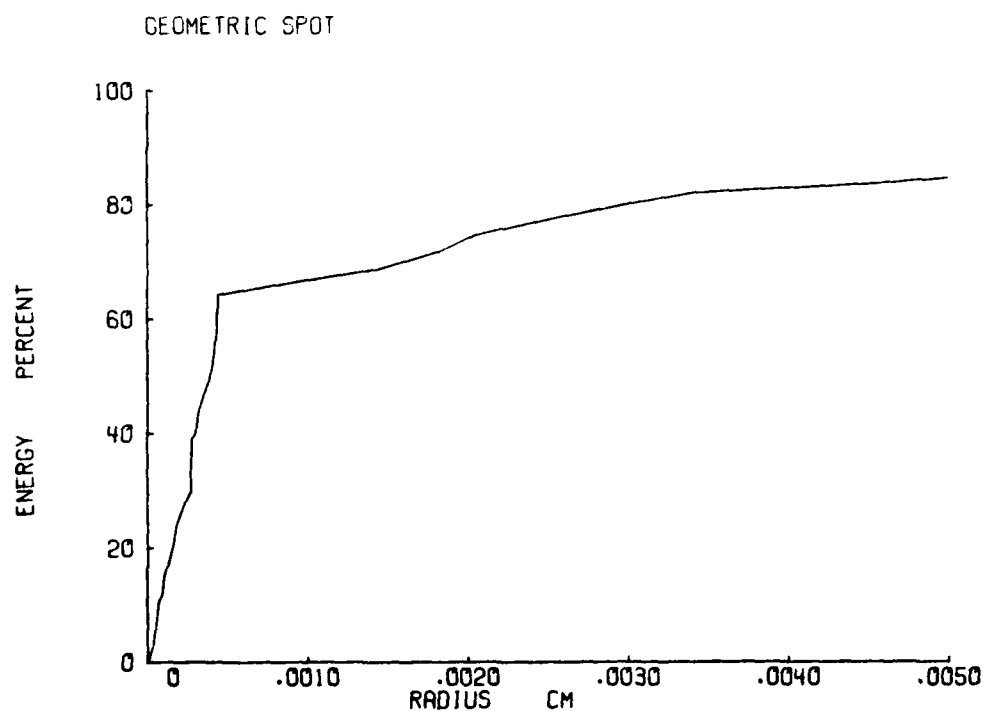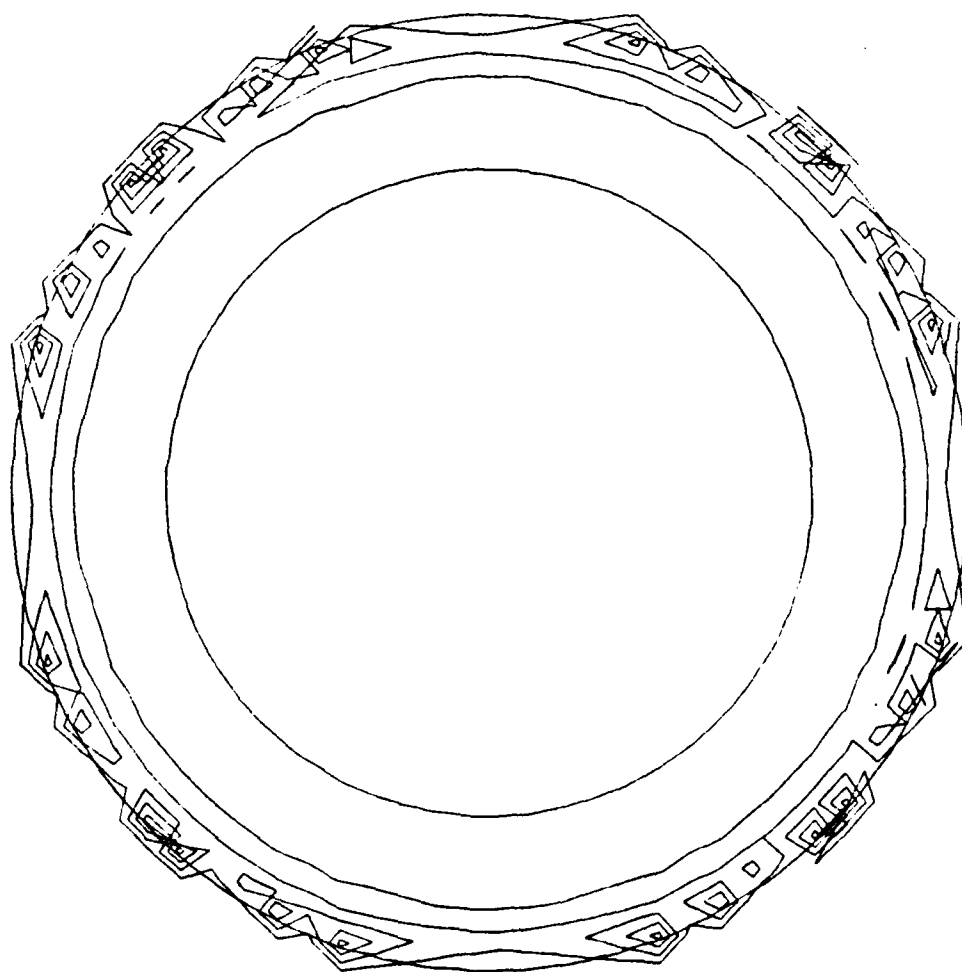
GEOMETRIC SPOT

Figure 27.   FALCON Radial Energy Distribution Plot
             for the Design.

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The wavefront in this case does turn in a little, although the peaks are less than ¼λ high (see Figure 28). It is exceptionally flat as can be seen in the isometric plot, Figure 29. The flatness of the wavefront leads to a Strehl ratio of .994.

A ray fan is useful as a visual indication of the color correction. The FALCON ray fan can be scaled in linear measure or in OPD (wavelengths). A ray fan is shown in both forms in Figure 30. Since the field of view is so small, the fans are shown only at the zero field angle. It is clear that the color correction is excellent (perfect color and zero aberrations would produce a horizontal line across the abscissa). There is, however, a noticeable fifth order spherical aberration, the large curve of the fan at the edges of the pupil. In fact, the fifth and seventh order aberrations are given by FALCON as SA5 -.006176 and SA7 -.001305. Fifth order spherical aberration is dependent on the 4th power of the ray height, Y, at the exit pupil (31:295). Since the value of Y is so small in this case, a large 5th order aberration can be tolerated. Here, the SA5 is not affecting the shape of the wavefront except at the edge of the pupil and even so, the wavefront is still within the Rayleigh ¼λ criteria. (The 7th order spherical aberration is dependent on the 6th power of the ray height and the large value of SA7 is also tolerable.)

To evaluate this lens as to its design tolerances, the paraxial solves must be removed and replaced with the curvatures. Thus, SPY in line 8 is deleted and replaced with CV -1.423342 and PUY in line 9 with CV 1.883775. Small changes can then be introduced in one parameter at a time and the effects observed in the EFL, BF, aberrations and Strehl

CONTOUR STEP   .005

Figure 28.   WAMAP Wavefront Contour Plot for the Design.

Figure 29. Isometric Plot of Figure 28.

.0203 CM

WAVELENGTH

——————— .4965

– – – – – – .4765

— — — .5145

.200 WAVES
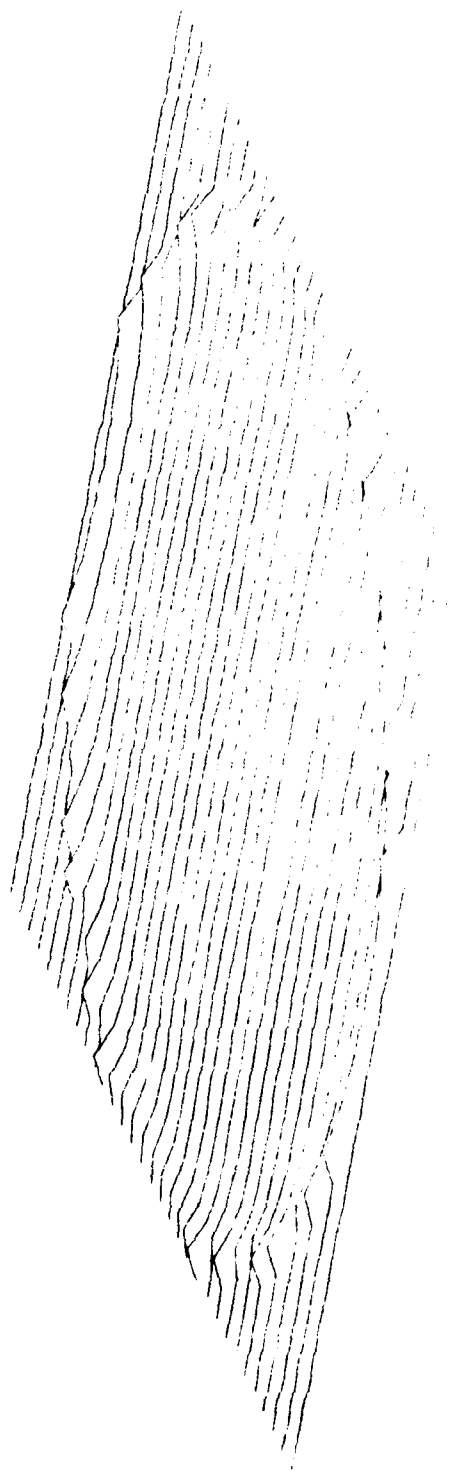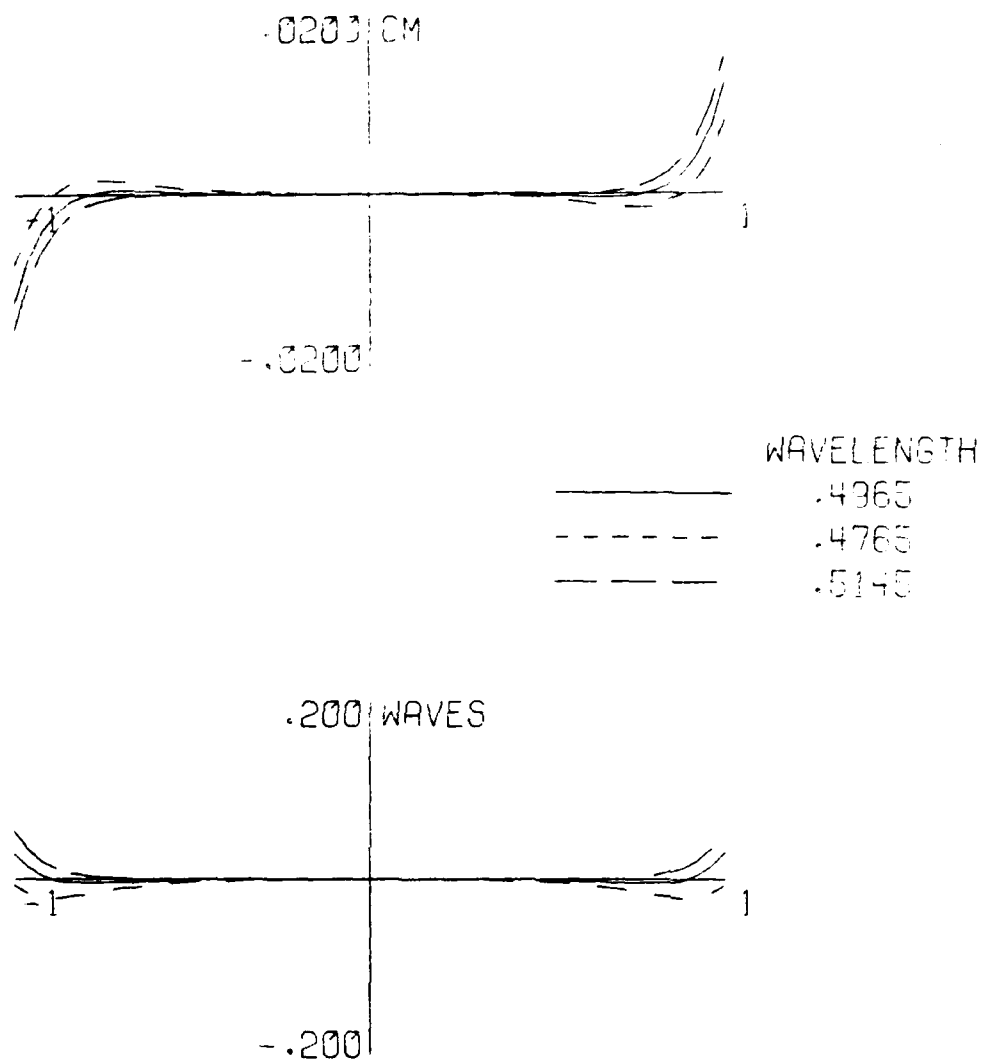
-.200

Figure 30. Tangential Ray Fan in Linear Measure (top)
and OPD (bottom) for the Design.

ratio. The parameters to be varied are the thickness after surface 4
(i.e., the distance from the secondary to the stop), the distance between

the primary and the secondary (the focus), small changes in the curvatures of the lenses, and the distance between the lenses.

The smallest magnitude change in the EFL and BF occurs for a change in the distance from the secondary to the stop or in the distance between the two added lenses. When either distance is changed by as much as ± .001cm, the EFL would change by no more than ± 150cm and the BF by ± 1.5cm. The smallest change was in a ± .001cm difference in the distance from the secondary to the stop where the EFL changed by only ± 30cm and the BF by only ± 0.3cm. In either case, the aberrations went up or down by no more than 10^{-4}cm and the Strehl ratio remained unchanged (at least to the third decimal place).

When the change in focus of the Questar was simulated by a change as little as ± .001mm (note: millimeters), the EFL changed by ± 140cm and the BF by ± 1.2cm. A change of ± 1% in the radii of curvature in any lens surface lead to a change in EFL of ± 500cm and a BF change of ± 6cm. Again, these changes did not appreciably change the aberrations. The wavefront plots and ray fans both exhibit the near flatness as the original design parameters did. In all cases, the Strehl ratio stayed around .994, never falling below .992.

Whenever a parameter was changed, the desired 2100cm focal length could always be restored by focusing the Questar. The BF would return to nearly the same 18cm and although the SA3 and PAC would rarely return to zero, they improved and remained close to zero in most cases. The real Questar focusses by a screw with 32 threads/inch. The primary could theoretically be moved as little as .001mm by turning the focus knob by 5^{0} or less. This is certainly not an impossible task. The

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Questar would have to be hand focused if this system were built and one would do so by observing the back focal length.

Tolerances on the position and centration of the lenses could be maintained within .001cm and a tolerance of ± 1% on the radii of curvatures of each lens is not an unreasonable value. It is not intended here to oversimplify the subject of tolerancing. Kingslake (19:2-6) makes it clear that tolerancing is not a matter to be overlooked and that in any design, the subject should be addressed carefully. The purpose of this section is not to show that the lens could be manufactured, rather this discussion on tolerance is to verify that it is within some expected production restrictions. One final point is worth mentioning. The two lenses designed here are both big enough in diameter and thick enough to be easily manufactured. The edge thickness of the positive lens works out to be .17cm and it need not be any larger in diameter since the transmitted beam is so small. The negative lens has an edge thickness of .509cm. One drawback to the final configuration is that four separate curvatures must be ground and the lenses will have to be marked so the users can identify which curve is the steeper.

It would not have been difficult to design this lens such that the curvatures on each lens would have come out symmetric. FALCON allows for parameter pickups and, for example, curve 7 could have been made equal (but opposite sign) to curve 6 and the same for curves 8 and 9. The number of variables would have been reduced but this design was completed without changing the lens thicknesses or the distances between the lenses once they were established. Control of the PAC would have been more difficult, however, since one would lose the freedom to bend

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either lens. In addition, the EFL and BF would have been difficult to control since the height of the axial ray and its angle of refraction at the last surface could not be fixed. The final result, however, would have been two symmetric lenses less expensive to manufacture.

Chapter closing remark: Many features of FALCON were not discussed in the design above because of the limited applicability of geometric optics to the design of diffraction limited systems. The discussion on the features of FALCON in Chapter II should fill the gap.

The lens designed here meets the design criteria by providing a diffraction limited Airy disc of sufficient diameter to fill the required number of cells on the detector. In addition, the five argon laser wavelengths used in the AFWL phase relationship algorithm were brought to very nearly the same focal point (within about ½ millimeter along the optic axis). The Strehl ratio of .994 exceeds the acceptable diffraction limited value of .80. A visual confirmation of the very nearly diffraction limited wavefront is seen in Figures 28 and 29. The wavefront is seen in the figures to fit well within a .02λ (λ=.4965 μm) thick reference sphere surface. This lens, if manufactured, would provide the required interference pattern discussed in Chapter III.

VI. An All-Refractive System

The system designed in the last chapter suffers from the fact that obscuration by the Questar secondary prevents smaller diameter apertures being placed closer together. Slightly smaller apertures of diameter d separated by 2d are desirable because a shorter focal length lens is needed to provide a 1mm diameter Airy disc and still retain the small number of fringes (5-7) in the interference pattern. An all refractive system would overcome this, having no central obstruction.

Choosing a 5cm diameter objective, apertures of 1.67cm diameter would be the largest that could be used and still be separated by 2d. A 1.67cm aperture requires a 13.76m focal length lens for a 1mm diameter Airy disc at .4965 μm. Thus, a 14m design focal length is a reasonable value. The objective will have to be achromatic so the separation of wavelengths can be kept to a minimum at the final lenses. The EFL of 14m and a BF near or equal to the BF achieved in the last chapter should be obtainable by adding only two lenses to the focal cone of the objective.

The lens deck can now be established:

```
0 SAY 2.5 YFANG .1 WV .4965 .4765 .5145 .5015 .4880
1 CV .1 CLAP 2.5 TH 1 SCHOTT BK6
2 CV -.1 CLAP PICKUP 1 TH .5 SCHOTT BASF53
3 PUY -.084465 CLAP PICKUP 1 PY .08
4 CV 0 TH .1
5 PUY -.05 TH .2 CLAP .25 SCHOTT BASF53
6 PUY -.03 PY .045 CLAP PICKUP 5
7 SPY .04 TH .2 CLAP PICKUP 5 SCHOTT BK6
8 PUY -1.8142E-03 CLAP PICKUP 5
9 CV 0 PY
10 END
```

The objective, lines 1-3, is a two element lens with curve 2 forming the contact between the first, BK6, element and the second, BASF53, element. The types of glass chosen was somewhat arbitrary since the Abbe number cannot really be calculated for the wavelengths used here. Thus, based on the experience gained in the design in the last chapter, glasses were chosen with as wide a separation in V number as practical. The PUY -.084465 sets a curvature on surface 3 so that the .4965 μm ray has an angle of -.084465° after refraction. This provides a focal cone of about 30cm long. The PY .08 sets the distance to the stop so that the ray intersects the stop at a height of .08cm. Curve 4, the stop, is placed to restrict the allowed cone of light that can enter the following lenses. The same technique was employed in the previous design.

This time, all curvatures on the two lenses following the stop are given by paraxial solves. The angles after refraction are fixed for surfaces 5 and 6. The distance from surface 6 to surface 7 is set so the ray from 6 hits 7 at a height of .045cm. Then surface 7 and 8 control the EFL and BF as before. Now, when the first and second surfaces of the objective are changed, everything after is automatically adjusted and the specified parameters are maintained.

With the above data, the results are: EFL 1400.0541, BF 22.0483, F/# 275.60, LENGTH 30.3456. The curvatures given by the paraxial solves are all good values and the aberrations are: SA3 2.520567, CMA3 .000230, AST3 0.0, DIS3 0.0, PTZ3 0.0, and PAC .746673.

After some juggling with curvatures 1 and 2, the SA3, CMA3, and PAC are reduced to 0.0, 0.00021, and .018002 respectively. The PAC is

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unacceptably high and altering curve 2 several times while bending the lens (curves 1 and 2) re-zeroes the SA3 but the PAC goes negative each time before the spherical aberration reaches zero. As before, this was corrected by a change in glass type. The first element was changed to K50. Now, altering curve 2 and bending the lens a number of times reduces both the SA3 and PAC to zero. The system still has the same EFL, BF, F/#, and LENGTH because of the paraxial solves on all the following surfaces. Curvatures 1 and 2 ended up at .065438 and -.062075. Curve 3 came out .01672, curve 5 .056878, curve 6 1.2745311, curve 7 -1.28112, and curve 8 .166087. These values are all reasonable for lenses this size ($\frac{1}{2}$ cm diameter) with no radius of curvature too small. A cross sectional view of the final configuration is shown in Figure 31.

A PARAX at each of the first three wavelengths gives a BF to be 22.0507cm at .4965 μm, 25.8200cm at .4765 μm and 25.7634cm at .5245 μm. The LChA given by BF at .4765 minus BF at .5145 is .0566cm. Notice that in this case all three wavelengths were not brought to focus within a few tenths of a millimeter of each other. The .4765 μm and .5145 μm foci are .0566cm apart but the .4965 μm focus is 3.769cm from the other two. This indicates there will be a region of best focus. FALCON will find the location of best focus when a BFR command (back focus of minimum radius focal spot) is added to a PUPIL command. (The command is PUPIL BFR LIST.) In this case, the position is 7.53cm left of the .4965 μm focus. At that point, the spot radius is reduced from .02166 to .02105cm.

4 CM

.250 CM

Figure 31. The Refractive System and Close-Up of the Two Lenses
at the Right.

The third order aberrations are now all zero except for a very small coma due to the non-zero allowed field angle. The ray fans readily show the decreased performance of this system from that of the last chapter. A very bad fifth order spherical aberration is evident from the large, curving fan edges (see Figure 32).

Figure 32. FANS Plot for the Refractive System.
Linear Measure (top) and OPD (bottom).

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FALCON gives the fifth order spherical as .040804cm. Time did not permit a restructuring of the system that may have reduced the fifth order aberration. (The FALCON aberration table, FORD can be listed showing the aberratio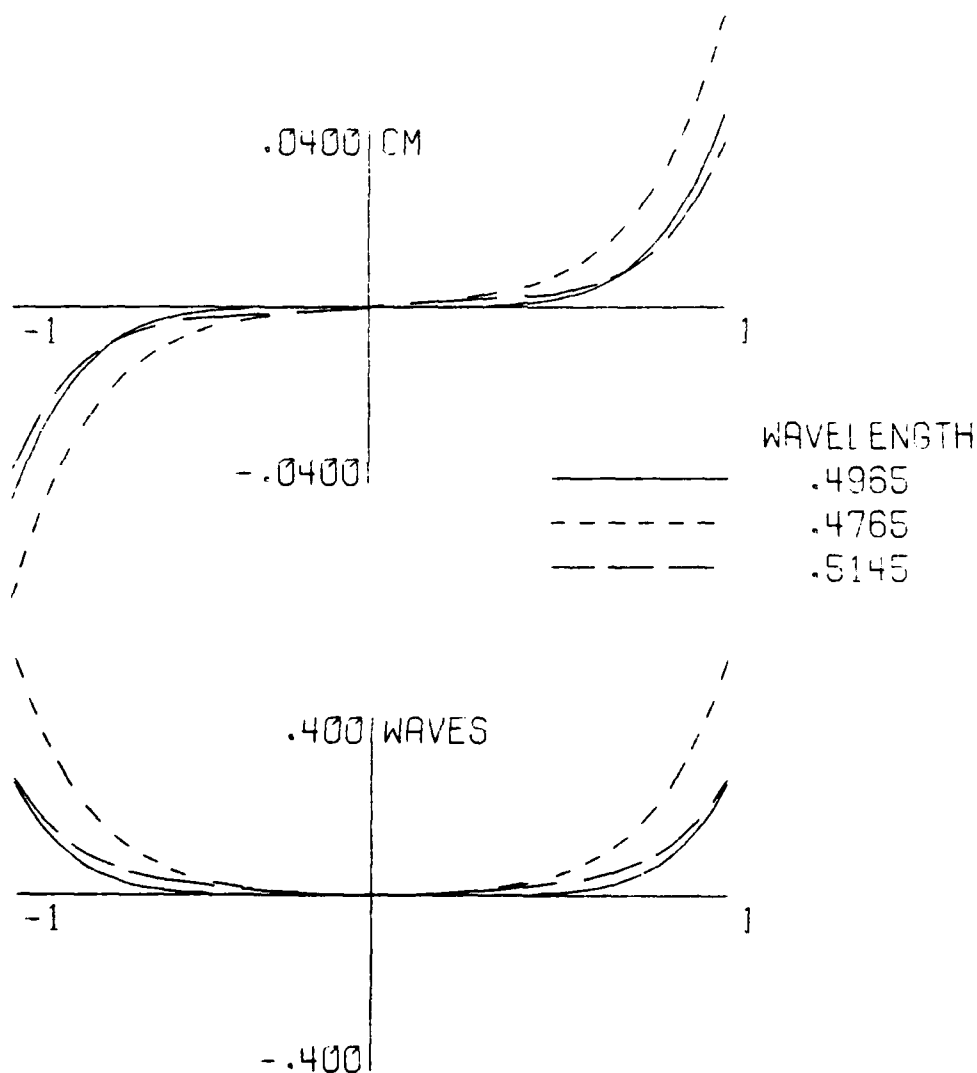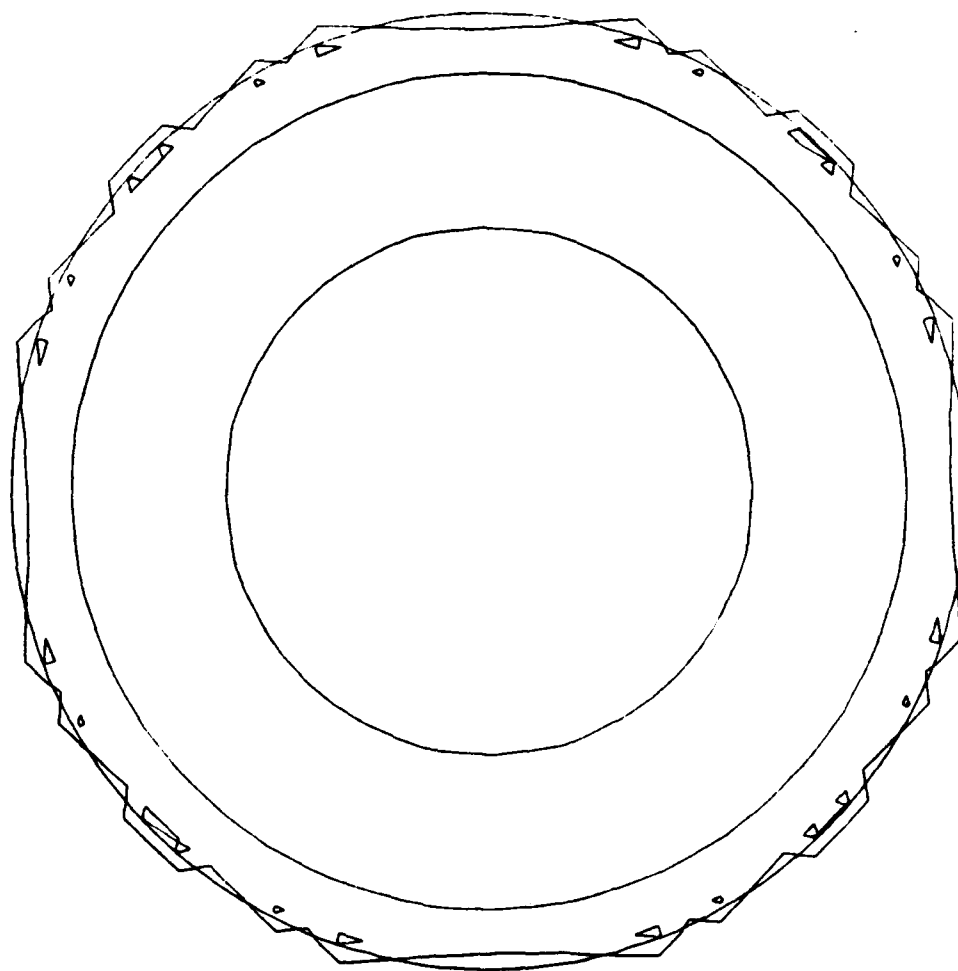n contribution at each surface. Had time permitted, the surface or surfaces contributing most to the fifth order aberrations could have been identified and corrections possibly made.)

The Strehl ratio is .826 as a result of the difference in foci and the bad fifth order spherical aberration. Nevertheless, the wavefront just fits between two reference spheres $\frac{1}{4}\lambda$ apart (at λ=.4965 μm) with only the extreme edges of the pupil contributing to the wavefront distortion outside the limit. See Figures 33 and 34.

This lens was conceived and designed in about four hours total time although not all at one sitting. It is clearly not as good as the design of the previous chapter but not as much time was devoted to it. It does demonstrate, however, that an all refractive design should be capable of doing the job.

Conclusions

The design using a Questar telescope was presented in Chapter V. After modeling the Questar, the necessary lenses were added to the focal cone to make a 21 meter effective focal length system. The two lenses added are 0.5cm in diameter and are of Schott BASF53 and BK6 glass, respectively. The curvatures can be found on page 52 and an illustration of the final system is shown in Figure 25. The Strehl ratio for the system was .994 and the wavefront contour and isometric plot of Figures 28 and 29 clearly indicate that the lens is diffraction limited.

CONTOUR STEP   .100

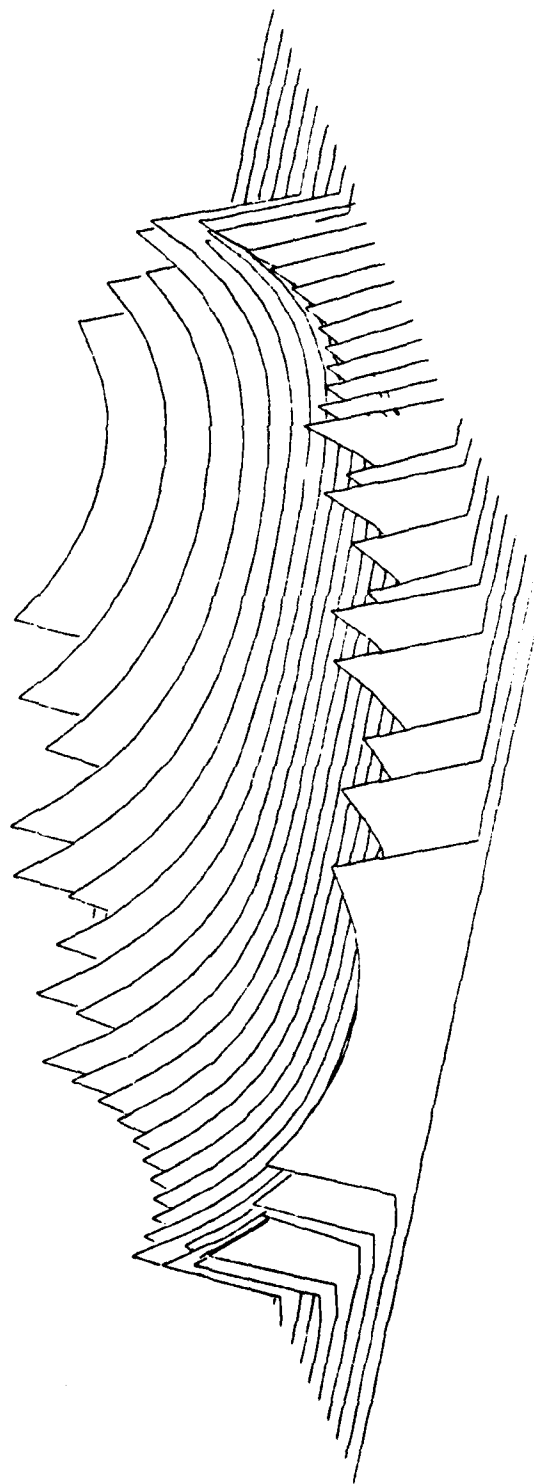Figure 33.   Wavefront Contour Plot for the Refractive
             System.

Figure 34. Isometric Plot of Figure 33.

The difference in back focus between the design wavelengths was held to just over a half millimeter, giving the lens exceptionally low chromatic aberration. The wavefront error due to fifth and seventh order spherical aberration was seen to be low. The ray fans, seen in Figure 30, show the focus error across the exit pupil to be within 0.2λ of the paraxial focal point. The lens very adequately fulfills the design requirements of Chapter III.

The all-refractive system developed in this chapter was designed to have a 14 meter effective focal length to use smaller apertures positioned closer together. The system was designed making extensive use of FALCON paraxial solves to simplify the initial specification of the lens. Spherical and chromatic aberration were then controlled by changing glasses. The resulting lens is illustrated in Figure 31. The refractor meets the design requirements although it clearly could use further refinement. The purpose, however, of the all-refractive system design was to verify that it could replace the Questar system, which it does.

Bibliography

1. Barnes, K. R. *The Optical Transfer Function*. New York: American Elsevier, 1971.

2. Born, Max and Emil Wolf. *Principles of Optics*. London: Pergamon Press, 1970.

3. Buchdahl, H. A. *Optical Aberration Coefficients*. London: Oxford University Press, 1954.

4. Conrady, A. E. *Applied Optics and Optical Design, Part 1*. New York: Oxford Press, 1943.

5. -----. *Applied Optics and Optical Design, Part 2*. New York: Dover Publications, 1960.

6. Dilworth, Donald C. "Current Status of the Synthesis of Optical Systems (SYNOPSYS) Lens Design Program," Proceedings of the Society of Photo-optical Instrumentation Engineers, 237: 5-10 (1980).

7. Gurbaxani, Brian. Air Force Weapons Laboratory Summer Work Report, 1982.

8. Hartshorn, C. R. "The Barlow Lens," *Amateur Telescope Making, Book 3*. Tennessee: Kingsport Press, 277-286 (1971).

9. Hecht, Eugene and Alfred Zajac. *Optics*. Massachusetts: Addison-Wesley, 1974.

10. Higdon, Charles E. An Optical Ray Tracing Program. White Oak, Maryland: Naval Ordinance Laboratory, 1974. (AD-787636).

11. Hopkins, H. H. "Introductory Modern Methods of Image Assessment," Proceedings of the Society of Photo-optical Instrumentation Engineers, 46: 2-18 (1974).

12. -----. "The Development of Image Evaluation Methods," Proceedings of the Society of Photo-optical Instrumentation Engineers, 46: 2-18 (1974).

13. Huber, Edward D. "An Intercomparison of Lens Design Computer Programs - A New User's Viewpoint," Proceedings of the Society of Photo-optical Instrumentation Engineers, 147: 45-56 (1978).

14. Jenkins, Francis A. and Harvey E. White. *Fundamentals of Optics*. New York: McGraw-Hill, 1976.

15. Juergens, Richard C. "The Sample Problem: A Comparative Study of Lens Design Programs and Users," Proceedings of the Society of Photo-optical Instrumentation Engineers, 237: 348-362 (1980).

16. Klein, Miles V. Optics. New York: John Wiley & Sons, 1970.

17. Kidger, M. J. "Calculation of Modulation Transfer Function (MTF) with Desk-Top Computers," Proceedings of the Society of Photo-optical Instrumentation Engineers, 274: 14-20 (1981).

18. -----. "The Use of O.T.F. in Optical Design," Proceedings of the Society of Photo-optical Instrumentation Engineers, 46:49-52 (1974).

19. Kingslake, Rudolf. Lens Design Fundamentals. New York: Academic Press, 1978.

20. Lea, Michael. Geometrical Optics. New York: Institute of Optics, University of Rochester, 1982.

21. Loomis, Donald C. FALCON User's Manual. Ohio: University of Dayton, 1981.

22. -----. "The Use of Paraxial Solves in Lens Design," Proceedings of the Society of Photo-optical Instrumentation Engineers, 147: 6-11 (1978).

23. MacDonald, John. "Comparison of Results of Various OTF Calculation Programs," Proceedings of the Society of Photo-optical Instrumentation Engineers, 46: 45-48 (1974).

24. Mandler, Walter. "Design of Basic Double Gauss Lenses," Proceedings of the Society of Photo-optical Instrumentation Engineers, 237: 222-232 (1980).

25. Marloth, Rudolf. "Specification and Evaluation of Optical Systems Having Discrete Detectors," Proceedings of the Society of Photo-optical Instrumentation Engineers, 54: 148-154 (1974).

26. Optics Guide 2. Catalog of the Melles Griot Company, 1981.

27. Palmer, J. M. Lens Aberration Data. New York: American Elsevier, 1971.

28. Peck, William G. "Distributed Computing for Optical Design," Proceedings of the Society of Photo-optical Instrumentation Engineers, 237: 2-4 (1980).

29. Peřina, Jan. Coherence of Light. New York: Van Nostrand, 1971.

30. Powell, Ian. "Lens Design Program," Proceedings of the Society of Photo-optical Instrumentation Engineers, 147: 37-44 (1978).

31. Smith, Warren J. Modern Optical Engineering. New York: McGraw Hill, 1966.

32. Thompson, B. J. and Emil Wolf. "Two Beam Interference with Partially Coherent Light," Journal of the Optical Society of America, 47: 895-902 (1957).

33. Weapon Feasibility Technology, Optically Phased Array Subtask. Kirtland Air Force Base, New Mexico: Air Force Weapons Laboratory.

34. Welford, W. T. Aberrations of the Symmetrical Optical System. London: Academic Press, 1974.

35. Wormell, P. M. J. H. and M. J. Kidger. "Optical Design Programs at Imperial College," Proceedings of the Society of Photo-optical Instrumentation Engineers, 237: 18-26 (1980).

Appendix A

Computer Program Survey

An investigation into optical design computer programs leads
one to three primary sources: universities, commercial firms, and
Government studies. Programs were found in all three sources and most
are briefly discussed below. It should be kept in mind that the author
had no experience with any of the programs prior to conducting this
search and, as such, the program descriptions are based solely on the
available literature.

The desired program, suitable for use at AFIT, should be one that
can handle the general optical design problem with as few restrictions
as possible. (The "general" design problem is considered as that problem
at the start of which it is not known how many or what type of optical
surfaces are needed. The program should be able to handle any config-
uration of refractive, reflective, and other types of surfaces.) Addi-
tionally, it will be necessary that the program be free of charge.
Time does not permit application for funding to purchase any computer
software.

Universities

The primary developer of optical design programs in universities
is Imperial College, London. They have four programs, each of varying
capability. VERSION 14 is an optimization program capable of handling
rotationally symmetric systems but only on a single optical axis (34:19).
VERSION 14 is therefore undesirable since tilted and decentered

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components cannot be used. The other programs are GEOMOTF, HETROTF, and G.R.T. They are programs for specific applications, the first for calculation of the geometric optical transfer junction (OTF), the second for finding the diffraction based OTF, and the third for providing ray tracing data. Thus, all programs at Imperial are not suitable as general design programs.

Work at other universities, i.e., the University of Arizona and the University of Rochester, indicate a predominance of programs purchased or supplied by commercial firms. One minor reference (13) led to a program called FALCON which, as it turns out, satisfies the requirements. FALCON is discussed in Chapter II.

Government

Government studies have led to the development of several optical design programs. It is surprising to note, however, that only a very few are available without charge. A program called RAYTRACE, written at the Naval Ordinance Laboratory, White Oak, Maryland (10) is one of those few. It is a general ray tracing program capable of handling nonrotationally symmetric systems and surfaces of shapes other than spherical. Unfortunately, the program makes little use of the ray trace data and has only limited output. Also, the input data to describe the lens seems unnecessarily complicated.

An image analysis program called POLYANA was mentioned in Marloth (25:151) which is an outgrowth of the design program POLYPAGOS. No reference was given in Marloth and no other source of information was found on either program.

It seems that most of all other design programs sponsored by Government projects whether through NASA or some other agency end up for distribution through COSMIC, the Computer Software Management and Information Center of the University of Georgia. At least four programs are available through COSMIC. FOLDP or Fortran Optical Lens Design Program can handle up to 100 plane, conic, or polynomial surfaces. It has a user-weighted merit function and has an automatic mode which reduces the merit function by adjusting the system parameters. It is written in FORTRAN IV for an IBM 7000 series computer. Price: documentation $71.00, program $1125.

LENSII is a second program from COSMIC. As described, it is similar to FOLDP but can handle only 49 surfaces. Written in FORTRAN IV for the IBM 360 series computer it is $1215.00. Documentation is $36.00.

GENOPTICS or General Optics Evaluation Program is described as having been developed as a "general aid for the analysis and evaluation of optical systems that employ lenses, mirrors, diffraction gratings, and other geometrical surfaces." The abstract goes on to say the program can handle up to 40 surfaces and that the program provides third order coefficients and output options such as spot diagrams, radial energy distributions, and modulation transfer function. This program is close to meeting the requirements but; price: $765.00, documentation: $23.50.

Last from COSMIC is AOSS, or Active Optics Simulation System. As described, the program goes beyond the general optical design and includes the NASTRAN structural analysis program. AOSS was defined for simulation of real optical systems down to the mounts and support

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system.   Program price: $825.00, documentation: $52.50.

Powell (30) discusses at length a program developed at the National Research Council (NRC) of Canada. The program is described as capable of handling many types of lenses including camera lenses, telescopic systems, telecentric systems, and systems with aspheric surfaces. The program has an optimization routine and provisions for handling zoom systems is under development. Perhaps the NRC will provide a name for the program. (Throughout Powell's entire article, the program is just that, the program.) It is not clear whether the NRC intends to distribute the program.

Commercial

By far the most computer programs were found in the commercial arena. The primary developers stand out in the field, each with a primary program upon which much of their effort is based. The primary developers are: Scientific Calculations, Inc. of Fishers, New York, Optical Research Associates, Pasadena, California, and the Genesee Computer Center of Rochester, New York. Their programs are ACCOS V, CODE V, and COOL/GENII, respectively. All three programs are very complete, powerful programs that have automatic design modes where the merit function is reduced by the program and an optimum design is produced. COOL/GENII is less capable only in that it has no plotting capability (13:50). Limited plotting is available through another program supplied by Genesee called GREY. These three programs are the subject of a quite good intercomparison by Huber (24).

In addition to ACCOS V, Scientific Calculations has a smaller program called SCIP designed for use on smaller computers (28:225). No details were available on SCIP. The Genesee Computer Center has seven programs of varying capability in addition to COOL/GENII and GREY. They are: COP, SYNOPSYS, SLAP, TROPAC, ZOOM SYNTHESIS, TPG, and FILMS (34:3). These programs are not general design programs with the single exception of SYNOPSYS. The author of SYNOPSYS, Don Dilworth, describes his program fully in a paper in Vol 237 of the Society of Photo-optical Instrumentation Engineers (6:5-10). His program was designed primarily for the more complex problem. Few default functions are available, the user must communicate his or her needs to the program using input commands. The program is available for lease or time-sharing through Genesee. The other programs from Genesee were not further investigated because of their limited usefulness.

Three other programs were mentioned in the literature (15). HEXAGON is a multicapability program in use at the Hughes Aircraft Company, OPUS is a program from the ITEK Corporation, and OSLO, a program for small computers at Sinclair Optics. These programs are not well described in the literature, so it is not clear if they are solely in-house programs or are intended for sale or lease.

In summary, only two programs were found that were (1) free and (2) capable of handling the general optical problem. RAYTRACE, from the Naval Ordinance Laboratory would have required extensive added programming to make use of the ray trace data it generates. FALCON is a complete design program and has extensive evaluation tables and

plotting capability. FALCON, needless to say, was the program chosen

for use at AFIT. FALCON is further described in Chapter II.

Appendix B

Seidel Aberrations

The following are the general formulas for the calculation of the Seidel aberrations taken from Lea (20):

FALCON Term	Aberration	Equation
SA3	spherical	$A \sum S_a i_a^2$
CMA3	coma	$A \sum S_a i_a i_b$
AST3	astigmatism	$A \sum S_a i_b^2$
PTZ3	field curvature	$A \sum \frac{c}{n}(\frac{n}{n'} - 1)H^2$
DIS3	distortion	$A \sum S_b i_a i_b - H(u_b'^2 - u_b^2)$

where

$$A = -\frac{1}{2n_k' u_{ak}'} \qquad \text{and} \qquad S_a = n(\frac{n}{n'} - 1)Y_a(i_a + u_a')$$

$$S_b = n(\frac{n}{n'} - 1)Y_b(i_b + u_b') \qquad i = Yc + u \qquad H = n(u_a Y_b - u_b Y_a)$$

and: i   is the angle of incidence at a surface.

Y   is the ray height at a surface.

c   is the curvature of the surface.

u   is the angle of the ray with respect to the optic axis before refraction.

n   is the index of refraction of medium left of a surface.

u'   is the angle after refraction.

n'   is the index of the medium right of a surface.

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subscript "a" refers to quantity from an axial ray.

subscript "b" refers to quantity from a chief ray.

subscript "k" refers to the last surface.

Summation is from surface 1 to k.

Spherical and chromatic aberration are the principle aberrations
one must deal with when working on or very near the optic axis. Coma,
astigmatism, and distortion are seen to go to zero on axis because i_b,
the angle of incidence of the chief ray at a surface, is zero on axis.
Petzval field curvature, zero on axis, is dependent on the curvature
of each lens surface rather than on the angle of incidence of the ray
at each surface. Field curvature then, is directly affected by what is
done to correct for spherical aberration since spherical aberration is
corrected by changing curvatures. One can expect, however, that there
will be little change in the field curvature near the axis.

Spherical and chromatic aberration must both be corrected
simultaneously. The chromatic aberrations are given by the following
third order formulae from Lea (20):

$$PAC = 2A \; \Sigma \; Y_a n i_a \left(\frac{dn}{n} - \frac{dn'}{n'^2} \right)$$

$$PLC = 2A \; \Sigma \; Y_a n i_b \left(\frac{dn}{n} - \frac{dn'}{n'^2} \right)$$

where: $dn = \left(n_{at\ short\ \lambda} - n_{at\ long\ \lambda} \right)$

$dn' = \left(n'_{at\ short} - n'_{at\ long\ \lambda} \right)$

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The parenthetical quantities $(\frac{dn}{n} - \frac{dn'}{n'})$ are basically the dispersion described by the Abbe number when working in the standard visual wavelengths. So chromatic aberration is controlled only for two wavelengths for which the Abbe numbers are known. In this study, the two wavelengths are really very close together and the Abbe number, as defined, has little meaning. The equations for chromatic aberration are still valid, however. Thus, chromatic aberration is controlled by choosing glasses with dispersive powers far enough apart that significant differences in OPD between the two very close wavelengths (.5145 μm and .4765 μm) can be achieved. The object is to keep the two rays as close together as possible throughout the lens. If glasses with less differing dispersions were chosen, large curvatures would be needed to cause separated rays to merge. Large curvatures would then introduce high spherical aberration.

The primary method to control the spherical and chromatic aberration is to bend the lens. Each surface of the lens is given an incremental change in curvature so that the power of the lens is held constant. The spherical aberration changes by bending the lens but the chromatic aberration does not. (In reality one will notice a change in chromatic aberration when bending a lens because bending is based on a thin lens approximation and not all lenses can be considered thin.) If it was observed that a high angle of incidence at one surface of a lens was contributing a large amount of spherical aberration to a system, then bending the lens effectively lowers the spherical aberration. One then alters the individual curvatures (or glass types) until the chromatic aberration is reduced. The spherical aberration will then

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need changing again so the lens will need further bending. The process

is continued until both aberrations are reduced.

Glossary

Axial Ray - That ray starting from the point on the object that is on the optic axis. The axial ray passes through the lens and crosses the axis again wherever an image is located.

Chief Ray - That ray starting at the object point off the optic axis. The chief ray passes through the center of the aperture stop. At the point where the axial ray crosses the axis, the chief ray defines the image height.

Curvature - The reciprocal of the radius of curvature.

Design Wavelength - The wavelength chosen from the range of wavelengths at which the lens will operate for the purpose of tracing rays and designing the lens.

Focal Cone - Term describing the region of space where all rays filling the circumference of the exit pupil converge to a focus.

Lens List or Lens Deck - Refers to the list of lens parameters in FALCON that completely describes the lens and object.

Meridian Plane - Any plane containing the optic axis.

Merit Function - A function consisting of aberration parameters chosen by the designer. The function is checked by the program through each cycle of automatic design to see if it is any smaller. The program continues making small changes until the function is as close to zero as possible.

Paraxial Focus - The point where paraxial rays come to a focus.

Paraxial Ray - A ray passing entirely within a small distance of the optic axis.

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Paraxial Solve - A subroutine used in FALCON to calculate the curvature
of a surface when the refracted or reflected ray angle or ray
height at the next surface is specified.

Primary - The main mirror in a reflecting telescope. The mirror doing
all the light gathering, and is the first element to receive
the light.

Reference Sphere - The sphere formed by a radius vector starting at the
paraxial focus extending to the exit pupil.

Sagittal Plane - The plane formed by the optic axis and the X-axis.

Secondary - The smaller mirror in a reflecting telescope and the second
element to receive the light beam.

Tangential Plane - The plane formed by the optic axis and the Y-axis.

VITA

William C. Welker, Jr., was born on 25 July 1953 in Enid, Oklahoma, the only son of W. J. and Nadine M. Welker. He graduated from high school in Enid in 1971 and attended Phillips University from which he earned the degree of Bachelor of Arts in Physics in December 1975. While at Phillips, he applied his talents as a photographical equipment repair technician at the area camera store. Upon graduation he studied astronomy for two years at the University of Nebraska, Lincoln, Nebraska. While at Nebraska he also taught astronomy labs, a photography course at Southeast Community College and physics labs at Nebraska Wesleyan University. He entered active duty in the Air Force in July 1978 and was commissioned from Officer Training School in October. He was assigned to Specialized Systems Program Office, Aeronautical Systems Division, Wright-Patterson AFB, Ohio, where he served as technical order manager for the HH-53H Night/Adverse Weather helicopter. He was selected to attend the Air Force Institute of Technology in October 1980. He entered the School of Engineering in June 1981 with the class of GEP-82D.

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A survey was made of existing optical design computer programs, and one selected for use at AFIT. The program selected is named FALCON, and a number of its capabilities are described. The program is used to develop a lens system whose effective focal length is 21 meters and whose overall length (first surface to focal plane) is about 45 cm. The purpose of the lens is to accept two laser beam samples from a source (i.e., a phased array telescope) and focus the beams to a diffraction limited spot. A standard

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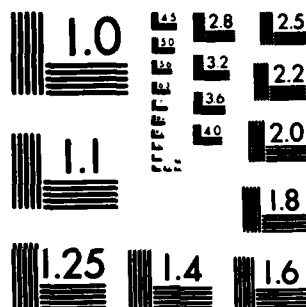
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$3\frac{1}{2}$ inch Questar telescope is used as the first optical element and its 1.27m focal length is extended some 16 times by adding lenses to the focal cone. A second design is made using entirely refractive optics to overcome a central obscuration problem caused by the secondary mirror of the Questar. FALCON is used exclusively to do all the design work.

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